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THE DEVELOPMENT OF THERMOPHILIC BIOHYDROMETALLURGYTO ENHANCE PRECIOUS METAL EXTRACTION FROM REFRACTORY SULPHIDE MINERAL HOSTS

FINAL REPORT

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EXECUTIVE SUMMARY

A three part study has been carried out to investigate the development of thermophilic biohydrometallurgy to enhance precious metal extraction from refractory sulphide mineral hosts.

In Part 1, a literature review was carried out on mineral leaching using the thermophilic bacterium Sulfolobus. Although little work has been done on using the thermophile for this application, the review indicates that the organism has some potential advantages as an alternative to the mesophilic bacterium Thiobacillus ferrooxidaus.

Part 2 of the study was an exploratory laboratory program to evaluate the potential of developing a Sulfolobus-based system within practical operating constraints. The results of this program did not show Sulfolobus to be a superior leaching organism for oxidizing two refractory ores and four refractory concentrates.

An economic comparison of a thermophilic and mesophilic pretreatment process in Part 3 of the study has indicated that capital and operating cost savings may be realized by using Sulfolobus if rapid oxidation kinetics at high pulp density can be demonstrated. Reduced cooling requirements for higher temperature operation offer only minor economic advantages.

Further studies are recommended to increase experience with working with Sulfolobus and to achieve a higher degree of acclimation of the culture to growth on refractory sulphides.

RESUME GENERAL

Trois plans d'étude ont été executes pour estimer le développement de la thermophilique biohydrométallurgie pour augmenter l'extraction des metaux precieux des minéraux sulphides refractaires.

En première partie une revue litteraire a été executée sur les minéraux de filtrage qui utilisent les bactéries thermophilique Sulfolobus. Meme si il y a en qu'un petit travail de fait utilisant la thermophilique pour cette demande, la revue indique que l'organisme a des potentiels avantageux comme alternatif pour les bactéries mesophilique Thiobacillus ferrooxidans.

La deuxième partie de l'étude consiste en un programme préliminaire en laboratoire pour évaluer le potentiel de développement de Sulfolobus de base un système contraint par l'opération pratique. Les resultats de ce programme n'ont pas montré que Sulfolobus était un organisme de filtrage supérieur pour oxyder deux minéraux réfractaires et quatre concentrés refractaires.

Une comparaison économique de la thermophilique et mesophilique ont un processus de pré-traitement en troisième partie de l'étude qui indique que le capital et l'économie du coût de l'opération pourraient être réalisés en utilisant Sulfolobus si l'oxydation rapide et cinétique à haute densité de pulpe peut-être démontrée. Reduire les besoins refraîchissant pour des opérations a haute temperature qui offrent seulement des avantages économiques mineurs.

Des études approfondies sont recommendées pour augmenter l'expérience de travail avec Sulfolobus et achever un plus haut degré d'acclimatation de la culture pour accroître les mineraux sulphides refractaires.

1.0 INTRODUCTION

1.1 Terms of Reference

Coastech Research Inc was awarded a contract by Supply and Services, Canada, DSS File No. 15SQ.23440-6-9159, to carry out the development of a biological leaching system to enhance precious metal recovery from refractory sulphidic materials using the thermophilic bacterium Sulfolobus. The contract was awarded under the Unsolicited Proposals Program of DSS.

1.2 Objectives

The main objectives of the study were:

(a) to carry out a literature review to identify the state-of-art in mineral leaching using Sulfolobus,

(b) to perform a laboratory experimental program to identify and, if possible, optimize critical parameters necessary to develop a thermophilic leaching process within practical operating constraints,

(c) to carry out a theoretical economic study to indicate the impact of a thermophilic leaching system on the commercial process economics of a Thiobacillus ferrooxidans-based system previously defined at Coastech.

1.3 Background

Biohydrometallurgical processes have been developed for the recovery of gold from refractory sulphide ores and concentrates. These processes, which utilize the extensively studied mesophilic bacterium Thiobacillus ferrooxidans, are recognized as having immediate commercial potential.

For some applications, mesophilic leaching systems may be unsuitable due primarily to excessive cooling requirements and slow reaction kinetics. For example, recent feasibility studies conducted at Coastech have indicated that T. ferrooxidans-based technology is not viable for two applications under consideration. In the first case, the need for a high degree of sulphide oxidation to liberate the gold and a relatively slow oxidation rate indicated a bioleach retention time of 105 hours in a continuous leach circuit. With the particular gold grade of the ore, this retention time did not provide attractive economics. The second case involved a high-sulphur concentrate requiring a high degree of oxidation. The absence of adequate volumes of cold cooling water at minesite to maintain a leach temperature of 35-40°C meant that refrigeration would be needed. Again, this cost would be excessive relative to the gold grade of the concentrate.

In addition to T. ferrooxidans there are several other known bacteria which can oxidize sulphide minerals. Some of these operate at higher temperatures (50-80°C). One particular bacterium, Sulfolobus, is considered by some to have a good potential of offering advantages with respect to the cooling and kinetic factors.

This report presents the findings of a program of work carried out with the objective of determining the technical and economic potential of a Sulfolobus-based bioleach system

to enhance precious metals extraction from refractory sulphide materials.

2.0 DEVELOPMENT OF THERMOPHILIC BIOHYDROMETALLURGY FOR THE TREATMENT OF REFRACTORY GOLD ORES - A LITERATURE REVIEW

2.1 Introduction

Since the discovery of the role of microorganisms in the oxidation of sulphide minerals and in the formation of acid mine drainage in 1947 (1), many workers have been active in attempts to develop practical, commercial processes which exploit microbiological reactions in mineral processing and extractive metallurgy. Several review articles which describe some of the potential applications of microbial reactions in the mining industry have appeared in the recent literature (2,3,4). Reactions which have potential include:

(i) the solubilization of metals from insoluble minerals,
(ii) the promotion of valency change through oxidative and reductive reactions,
(iii) the precipitation of metals from solution,
(iv) the recovery and/or removal of metals from process solutions and wastewater by sorption or accumulation,
(v) the destruction of toxic constituents in solution,
(vi) the modification of mineral surface properties to promote mineral separation.

Of the potentially useful reactions, it is the solubilization, or leaching, of metals which has attracted the most attention of researchers over the past 40 years. For most of this time, the leaching of copper and uranium has received the most interest and represents the only current use of microbial technology in the industry. However, although the recovery of these two metals by heap leaching, dump leaching, and ore remnant leaching has been widely practiced, these applications are essentially

secondary or scavenging operations. Despite the considerable progress made in the understanding and development of microbiological leaching reactions, processes have not yet been used for primary metal production.

One of the most rapidly developing areas in microbiological leaching technology is the use of bacteria in the treatment of refractory sulphidic gold ores. These are ores in which gold is locked up inside host sulphide minerals such as pyrite and arsenopyrite. Often the gold is so finely divided that even extremely fine grinding does not liberate the metal. Consequently, conventional extraction techniques, such as leaching in cyanide solution, achieve poor recovery. For such ores, an oxidation pretreatment is required to break down the sulphide minerals and expose the gold for recovery. Addison (5) provides a review of the problems associated with the processing of refractory ores. Traditionally, roasting has been used for pretreating refractory ores. Hydrometallurgical processing routes, such as leaching in autoclaves under conditions of high temperature and pressure, are now used commercially and are becoming more widely accepted.

Microbiological leaching processes for the pretreatment of refractory gold ores have been studied for a number of years (6-14). The technology has been successfully piloted on a large scale (15) and commercial application is considered to be imminent in a number of countries. The basis of the technology is the capability of the bacterium Thiobacillus ferrooxidans for chemolithotrophic growth in acidic environments. This bacterium, which has been the most thoroughly studied organism for leaching applications, obtains energy from the oxidation of ferrous iron and reduced sulphur compounds. It is therefore able to oxidize gold-bearing sulphide minerals, such as pyrite and arsenopyrite, to liberate the precious metal for recovery.

In addition to T. ferrooxidans , which has an optimum temperature range of 30-37°C, there are other microorganisms capable of oxidizing sulphide minerals. Some of these organisms are moderately or extremely thermophilic, ie. they operate at higher temperatures (45-90°C) than the mesophilic T. ferrooxidans. It is not the purpose of this review to provide a detailed account of all of these organisms and their potential in ore treatment. Several recent review articles and technical papers can be found on this topic (2,16-21). One particular organism, the extremely thermophilic Sulfolobus , is the subject of this review.

2.2 Sulfolobus

Sulfolobus was originally isolated and described as a new genus of bacteria by Brock and co-workers (22). They found that the organism has generally spherical cells and is a facultative autotroph, able to grow both autotrophically on sulphur and heterotrophically on yeast extract. The temperature range for growth was around 55° to 85°C although slight growth occurred at 40° to 45°C. The optimum temperature range was 70° to 75°C. The pH range for growth was from about 1 to 5.9, with an optimum between 2 and 3. The bacteria was described as having no close relationship with any previously described bacteria, either heterotrophic or autotrophic and was suggested as being an important geochemical agent in the production of sulphuric acid from sulphur in high temperature hydrothermal systems. S. acidocaldarius has been shown to be able to oxidize large amounts of ferrous iron in hot, acid springs (23). Ferrous iron oxidation can apparently take place in the absence of other oxidizable substrates (23).

Sulfolobus and closely related species have been isolated from acidic thermal waters such as at Yellowstone National Park (22,24), deep-sea hot vents (25) and coal piles (26). Despite its restricted habitats, Sulfolobus is world-wide in its distribution (24). Wiegel and Ljungdahl (16) list the validly published Sulfolobus organisms as Sulfolobus acidocaldarius, S. brierleyi and S. solfataricus .

Brock (25) has provided a comprehensive study of Sulfolobus and its habitat, ecology and growth. The organism is the most thermophilic autotroph available in pure culture. In one spring at Yellowstone, a massive Sulfolobus population was found at a pH of 0.9. Growth in the laboratory was not found to be any better if cultures were shaken or aerated, although growth is stimulated if the gas phase is enriched with 5% CO_2 in air. Growth was found to be stimulated by the addition of yeast extract (0.1%), although sulphur oxidation was inhibited.

Sulfolobus has been little studied with reference to its potential application in metal extraction from sulphide minerals. Much of the published work is related to the oxidation of copper sulphide minerals such as chalcopyrite, $CuFeS_2$, and the potential for the extraction of copper from waste or concentrates (18,20, 27-33). Early interest in Sulfolobus also centered around its ability to oxidize molybdenum sulphide (18, 27, 28, 29, 30, 34). More recently, work on other sulphide minerals such as pyrite, FeS_2, pyrrhotite, FeS and pentlandite, (Fe,Ni)S, covellite, CuS, sphalerite, ZnS, millerite, NiS, and arsenopyrite, FeAsS, has been described (35,36,37). Sulfolobus has also been proposed for use in the desulphurization of coal (38, 39).

Very little direct reference to work to investigate the potential of Sulfolobus in the treatment of refractory gold

ores has been found in the literature although the possibility has been discussed (36). Hutchins and co-workers (40) have presented data on the possible treatment of carbonaceous and sulphidic gold ores and indicate that superior oxidation kinetics can be achieved compared with mesophilic systems. The above referenced and other works on the oxidation of sulphide minerals and potential applications do, however, contain some useful practical information and findings that could apply to refractory gold ore treatment.

There is controversy regarding the ability of Sulfolobus to withstand an abrasive leaching environment. Some regard Sulfolobus strains as some of the most robust organisms for leaching (16, 41). Weiss (41) reports that the cell wall is extremely rigid and is able to withstand physical stress. Norris and Parrott (36) report, however, that particular strains will grow autotrophically only in static rather than agitated culture. This may be related to the ability of some strains to withstand the stress of an agitated leach system. Similarly, Marsh and co-workers (35) concluded that the rate and extent of mineral dissolution depends on the strain of Sulfolobus. These workers found that iron and sulphur oxidation by a culture collection strain of S. acidocaldarius could not be demonstrated. A strains of S. brierleyi was found to require yeast extract for ferrous iron and pyrite oxidation. In contrast, their Sulfolobus (strain Lake Myvam), probably S. acidocaldarius, oxidized pyrite completely, with or without the presence of yeast extract. Observation of differences between strains has also been made by other workers (37) who found that differences in the ability to leach sulphide minerals were often greater for strains related to the same species than differences for strains related to different species.

Norris and Parrott (36) found that Sulfolobus can tolerate greater acidity than T. ferrooxidans. This has considerable significance for the treatment of highly pyritic concentrates for which low-pH solutions would be generated. These workers also concluded that tolerance to cations is similar to that of mesophiles and moderate-thermophiles. Rapid iron oxidation was obtained in the presence of 18 $g.L^{-1}$ Cu, >30 $g.L^{-1}$ Fe^{3+} and >35 $g.L^{-1}$ Fe^{2+}. Iron oxidation rates up to 2 $g.L^{-1}.h^{-1}$ at pH 1.5 were achieved.

In their comparison of mesophilic and thermophilic bacteria in leaching sulphide minerals, Groudeva and co-workers (37) suggested that mesophiles seem more suitable for leaching operations than thermophiles. This is in contrast to the work of Norris and Parrott (36) who conclude that higher oxidation rates and metal yields are an advantage of thermophilic leaching at pulp densities of 1-10% solids. This view is supported by others (20) who found that the energy of activation of a thermophilic culture (species not specified) was lower than for T. ferrooxidans. This, together with the difference in optimum temperature, contributed to higher reaction rates achieved with the thermophiles for growth on chalcopyrite. Other workers have found that Sulfolobus is more effective in sulphide mineral leaching than the mesophilic thiobacilli (27,33,34).

Work by Kargi and Robinson (38,39) on applying Sulfolobus in the desulphurization of coal provides some of the most practical data and information as to the practical application of this organism.

Experiments were carried out to investigate the influence of certain process variables and environmental conditions on the rate and extent of pyritic sulphur removal

from coal. More than 90% of the inorganic sulphur content of a bituminous coal (4.1% total sulphur) was removed by S. acidocaldarius. Nutrient concentrations, particularly N/P and N/Mg ratios were found to affect oxidation rates. External CO_2 addition did not affect pyritic sulphur removal at 10% pulp density, although increasing CO_2 may improve rates at higher pulp density and/or pyrite concentrations.

Optimum temperature and pH values resulting in the maximum rate of sulphur leaching were found to be 70°C and 1.5 respectively. Pyrite oxidation rates were found to increase with increasing initial cell concentrations, with an optimum of 10^8 cells/cm² of coal surface or 10^{12} cells/g pyrite in coal. Oxidation rates increased with decreasing particle size, with twice the oxidation rate being achieved at 48um as at 270um. Oxidation rates were found to be proportional to pulp density up to 15% solids, with an optimum at 20% solids. No increase in rate was observed at pulp densities over 20%.

The major advantage of using S. acidocaldarius over T. ferrooxidans for the desulphurization of coal are claimed to be the improved rate of chemical oxidation of pyritic sulphur by ferric iron produced by microbial action; reduction in the cooling requirements at high cell and coal concentrations; and reduced contamination of the reaction medium at the high temperature and low pH.

2.3 Conclusions

The study of Sulfolobus and related bacterial species for mineral leaching applications is still a relatively new field. However, despite some uncertainty in nomenclature and apparent differences in oxidative capability, certain

strains clearly have utility and some workers have achieved significant experimental progress.

Early work on copper minerals, particularly the recalcitrant chalcopyrite, indicated that higher metal yields or more extensive oxidation may be possible with Sulfolobus compared with T. ferrooxidans. This has also been shown to be the case with pyrite, particularly with the work done on coal desulphurization. Although there is no specific study reported in the literature on the use of Sulfolobus for the treatment of refractory gold ores and concentrates, there is no apparent reason why the thermophilic system could not provide as good or a better alternative to the well developed T. ferrooxidans-based systems. The potential advantages of the high temperature system are better oxidation kinetics and reduced cooling requirements. Sulfolobus also possesses the low pH and high cation tolerance required for practical application.

The rapid oxidative ability of Sulfolobus in high-density pulps is still in question. Low-sulphur coal pulps of up to 20% solids have been successfully leached but the oxidation of high-sulphur, high-density mineral pulps has not yet been shown to be viable.

Considerable research and development work is required to fully evaluate the Sulfolobus leaching system for the treatment of refractory gold ores. Detailed study of, and determination of the key process variables and their optimum values needs to be carried out so that significant technical and economic comparison can be made with the extensively studied T. ferroxidans system.

3.0 LABORATORY PROGRAM - EXPERIMENTAL METHODS

3.1 Ores and Concentrates

Two ores and four concentrate samples were used in Sulfolobus evaluation tests. All were refractory to gold recovery by cyanidation. Table 1 provides head assay data for the test materials. Two of the concentrates, NN and CIN, and both ores, NAM and RD, contained pyrite as the dominant sulphide species, with small amounts of arsenopyrite. Two of the concentrates, MET and CP, had high arsenopyrite contents. All materials were ground as required to 75-90% passing 200 mesh for testing.

3.2 Organisms and Growth Media

The culture of Sulfolobus, probably S. acidocaldarius, isolated from the acidic drainage of a pyritic coal pile (26), was provided by Dr. P.R. Norris, University of Warwick, U.K.

The cultures of Thiobacillus ferrooxidans were selected from Coastech stock cultures previously maintained on pyrite and/or arsenopyrite concentrates.

A growth medium containing (g/L) $(NH4)_2SO_4$ (2.1), $MgSO_4$ (0.18), K_2HPO_4 (0.18), KCl (0.04), and $Ca(NO_3)_2.4H_2O$ (0.004) was used for Sulfolobus tests except where otherwise stated. For tests using T. ferrooxidans, a medium (CR-2) containing (g/L) $(NH_4)_2SO_4$ (3.0), $MgSO_4$ (0.25), K_2HPO_4 (0.25), KCl (0.05), and $Ca(NO_3)_2.4H_2O$ (0.005) was used.

3.3 Leach Test Procedures

With the exception of one agitated tank leach comparison, all leach tests were carried out using various weights of ore or concentrate suspended in 50 mL of growth medium in 250 mL baffle bottomed Erlenmeyer flasks (Wheaton Scientific). Flasks were incubated on reciprocating shakers at 64°C/120 rpm (Orbit Environ Shaker Model 3527, Lab-Line Instruments Inc) for Sulfolobus tests and at 33°C/140 rpm (Orbit Shaker No. 3590, Lab-Line Instruments Inc) for T. ferrooxidans tests. Static tests on Sulfolobus were conducted using a stationary incubator maintained at 64°C (Model 1520 Incubator, VWR Scientific Inc).

For each test, pulp pH was stabilized with sulphuric acid prior to inoculation with a culture (4-10% by volume) previously grown on the test ore or concentrate. Flasks incubated at the higher temperature were sealed with aluminum foil to minimize evaporation. Losses due to evaporation were made up frequently.

Tank leach tests were carried out in 5L baffled, plexiglas reactors agitated by pitched-blade turbine impellers driven by vari-speed motors. The temperature of the leach pulps was maintained at 69°C using immersion heaters. Air was introduced under the impellers at approximately 0.8 L/min. Carbon dioxide was added to the air stream of one tank by means of a peristaltic pump to give 1-5% by volume. Water was added frequently to make up for evaporation losses.

Flasks and tanks were monitored periodically for pH, Eh and leached iron. Leached iron was routinely determined as soluble iron, Fe(S), by direct analysis of leachates by atomic absorption spectrophotometry (AA). In addition, leached iron was periodically determined as total leached

iron, Fe(T), by AA following dissolution of iron which had leached but subsequently precipitated under specific conditions of pH and Eh at the higher temperature. Dissolution of precipitated iron was accomplished by adding 1 mL of 5N HCl to a representative 1 mL sample of pulp for 30 minutes.

Eh values were measured and reported as mV relative to a silver-silver chloride electrode.

All assays of head samples of ore and concentrates, tank leach residues and cyanidation products, were carried out at CDN Resource Laboratories, Delta, B.C. by standard procedures.

3.4 Cyanidation Tests

Cyanidation tests were performed on NN head concentrate and bioleached residue using standard 24 hour bottle-roll procedures. 1g/L sodium cyanide was added together with lime to maintain protective alkalinity.

4.0 LABORATORY PROGRAM - RESULTS AND DISCUSSION

4.1 Amenability of Ores and Concentrates to Sulfolobus Oxidation

The objective of the laboratory program was , at the outset, to evaluate the potential for developing a Sulfolobus-based oxidation system within practical operating constraints. This requires demonstration of fast oxidation kinetics; operation at high pulp density; tolerance to low pH; tolerance to high metal concentrations; selective oxidation of gold-bearing sulphides; and high gold recovery following biooxidation pretreatment. The initial experimental plan was to perform preliminary shake-flask tests on three refractory concentrates and to select the most amenable for use in the main test program. Amenability was defined as the subject material being able to support a high bacterial yield and being oxidized to a high degree.

The above plan did not proceed as expected as none of the initial concentrates evaluated (CIN, NN, MET) proved to be readily amenable. Eventually, four concentrates and two ores were tested. However, even after several serial transfers, no one material could be selected as being significantly more suitable for exclusive evaluation.

Over the duration of the program, all six refractory materials were used in several shake flask tests to evaluate the various process parameters. Table 2 provides a summary of the best Sulfolobus leach data obtained for each ore/concentrate. Typical leach data obtained for T. ferrooxidans tests are shown for comparison.

In all cases, the T. ferrooxidans data is superior to the Sulfolobus data. This is particularly the case for the

two high-arsenic concentrates, MET and CP. In these two cases, inhibition of leaching by soluble arsenic may account in part for the poor performance.

4.2 Iron Precipitation Tests

A series of non-inoculated tests was performed to determine the degree of iron precipitation that could occur at the higher leach temperature. Eight test shake flasks were set up; four contained approximately 10 g/L ferrous iron as ferrous sulphate and four contained a similar concentration of ferric iron as ferric sulphate. For both sets of flasks, two were adjusted to pH 1.9 and the other two to pH 1.2. One flask of each pH pair contained the standard addition of nutrient salts. The flasks were placed on the shaker at 64°C and sampled at 1, 2 and 4 days for soluble iron, Fe(S).

Table 3 provides the results of the tests and Figure 1 shows the decrease in soluble iron due to precipitation, with concentrations expressed as a percentage of the original concentration.

The results of the precipitation tests show that precipitation of iron was the greatest at the higher pH and in the presence of the nutrient salts. Up to nearly 50% of the iron precipitated in one test (ferric iron, pH 1.9, nutrients). At the lower pH and with salts added, around 22-25% of iron, either as ferrous or ferric, precipitated. It can be seen in two cases that solutions that were originally ferrous gave a higher degree of precipitation than the corresponding ferric solution. No attempt was made to determine the degree of ferrous iron oxidation taking place in these tests.

4.3 Effect of Agitation

Figure 2 shows the change in pH due to sulphide oxidation against time for agitated and static shake-flask leaches of NN, MET, and CIN concentrates at 4% solids. Sulphide oxidation took place in all flasks and at a faster rate with agitation. Figure 3 shows a comparison between shake-flask and agitated tank for the leaching of NN concentrate at 10% solids. The results of the two leaches were essentially the same and show that the improved leaching environment of an aerated, agitated tank did not improve rates, nor did the more violent agitation conditions of this system have a detrimental effect on rates.

4.4 Effect of Initial pH

The effect of initial pH on leaching performance was studied for NN and CIN concentrates. For NN concentrate at 5% solids, the initial pH had little effect on the rate of iron leached in the pH range 1.6 to 3.0 (Figure 4). The lower soluble iron concentrations for the tests initiated at pH 2.5 and 3.0 are probably due to to iron precipitation at the higher pH rather than to a pH effect on kinetics. The complete date obtained from the tests are shown in Table 4.

Figure 5 shows the change in pH during leach tests on CIN concentrate at 5% solids initiated in the pH range 1.6 to 2.9. Again, the initial pH had little influence over the leach result, with all leaches terminating at a similar pH.

4.5 Effect of Nutrient Concentration

A series of ten leach tests was performed on NAM ore at 10% solids to evaluate the effect of nutrient composition on leach performance. The nutrient compositions were varied by changing the concentrations of $(NH_4)_2SO_4$, K_2HPO_4 and $MgSO_4$ as shown in Table 5. Concentrations of KCl and $Ca(NO_3)_2.4H_2O$ were kept constant at 0.04 and 0.004 g/L respectively.

There was very little difference in the quantity of iron leached in any of the tests after 25 days, with iron extraction (total) values in the range 52-58%. An exception was 44% extraction for test #5 but this difference is not considered to be significant.

These results are contrary to the findings of others (22) who showed that N/P and N/Mg ratios could have a marked effect on pyrite removal rates from coal using Sulfolobus.

4.6 Effect of Pulp Density

Tests to evaluate the effect of pulp density (% solids) on leaching by Sulfolobus were carried out on CIN concentrate, NN concentrate (2 series), CP concentrate, MET concentrate, and NAM ore (2 series). For CIN and NN concentrates, tests were also carried out using T. ferrooxidans for comparison.

The results of the leach tests on CIN and NN concentrates using Sulfolobus and T. ferrooxidans are given in Tables 6-9 and in Figures 6 and 7. The effect of pulp density on iron leach rate for the two concentrates are shown in Figures 8 and 9. In both cases, the oxidation rates

and extent of oxidation were substantially higher for the mesophilic system.

The results of the the other pulp density tests series using Sulfolobus performed on NN concentrate (2nd series), CP concentrate, MET concentrate, and NAM ores (2 series) are given in Tables 10-14 respectively. It is interesting to note that in all the data presented on pulp density and other tests, Eh values during leaches with Sulfolobus were usually in the 310-410 mV range. This contrasts with the T. ferrooxidans data in which Eh values usually rise to over 600 mV once active oxidation is established. Thus, in the mesophilic system, the leach solution will have a high ferric/ferrous ratio. In the thermophilic system, ferric concentrations are low and this may contribute to the lower oxidation rates observed in this study due to a low level of ferric iron activity.

For leach systems using T. ferrooxidans, we find that, following process optimization, pulp densities of around 30% solids are practical for ores. For concentrates, 20-25% solids is usually employed to reduce metal and acid loadings in the bioleachate. The results given for CIN and NN concentrates using Sulfolobus show that oxidation rates do not compete with the mesophilic system. More work is required to improve oxidation rates, particularly in high density pulps. P.R. Norris (personal communication) has obtained higher pyrite oxidation rates with Sulfolobus compared with T. ferrooxidans at very low pulp densities but observes poor rates as densities are increased over 2% solids in stirred reactors. Other workers (E.B. Lindstrom, personal communication) have not observed a detrimental effect of highly agitated pulps on rate in stirred reactors but have found the leaching of an arsenopyrite-containing concentrate limited by a pulp density effect due to an inhibition of oxidation by soluble arsenic above 1.5 g/L.

4.7 Effect of Carbon Dioxide

The results of tank leach tests on NN concentrate conducted with and without the addition of carbon dioxide to the air supply are shown in Figure 10 and Table 15..

Initially, carbon dioxide was added at a rate to give approximately 5% by volume of the air sparged under the impeller. Iron leach rates in the tank with the CO_2 addition were lower than with air alone. Reducing the CO_2 content to approximately 1% at 526 hours did not impact the rate of leaching.

These results were not expected. As previously discussed, carbon dioxide addition has been found to be beneficial in improving pyrite oxidation rates and it was thought that the tank tests would have shown that the poor results obtained in the shake-flask work may have been due to a carbon dioxide limitation.

4.8 Effect of Sulfolobus oxidation on Gold Extraction

Due to the limited progress made in achieving the original objectives of the experimental program, a detailed study of the effect of oxidation on gold recovery by cyanidation was not carried out. Only one cyanide extraction tests was carried out on a residue partially oxidized by Sulfolobus.

Table 16 gives the results of the tank oxidation test conducted on NN concentrate using Sulfolobus without carbon dioxide addition (Tank 1 in Table 15). At the termination of the test, 55.2% of the sulphide had been oxidized. Gold recovery from the oxidized residue was 39.4% compared with

13.6% from the untreated concentrate. Tables 17 and 18 give details of the cyanidation tests performed on the head and residue samples.

Thus, biological oxidation was effective in increasing gold recovery although recovery would obviously need to be considerably higher for process viability. It can be assumed that a higher degree of oxidation would have produced a correspondingly higher gold recovery. What is not known is whether the Sulfolobus system can achieve selective oxidation of the gold-bearing sulphides as is common for the T. ferrooxidans system. This allows high recovery of gold without the need for complete sulphide oxidation.

5.0 PROCESS ECONOMICS COMPARISON

5.1 Introduction

A preliminary economic comparison between a thermophilic and a mesophilic leaching system for the pretreatment of a refractory ore has been carried out. The basis of the comparison was a detailed engineering study recently carried out at Coastech for a T. ferrooxidans system to treat 350 tpd of a refractory gold ore grading 32g/tonne Au. On the basis of bench scale and pilot plant testwork conducted on the ore in our laboratory using T. ferrooxidans, detailed process flowsheets were designed with the schematic arrangement shown in Figure 11 and the design criteria given in Table 19. The capital and operating costs for this base-case processing plant are shown in Table 20. The costs shown are for the total plant (crusher to bullion) and for the biooxidation section only (bioleach tanks, solid-liquid separation, neutralization and cooling).

In the absence of conclusive data either from this or any other laboratory study, the comparison was made with the assumption that the process for the two systems would be essentially the same and that any differences in process details could be ignored for costing purposes. It was further assumed that the primary benefits to be derived from higher temperature operation would be reduced cooling costs and improved oxidation kinetics. The impact of these two factors on the base-case economics will be discussed in turn below.

5.2 Cooling Considerations

Oxidation of sulphide is an exothermic process. In both mesophilic and thermophilic systems, heat generated

from the oxidation of 70% of the feed sulphur (base case) is sufficient to cause the pulp temperature to rise well above the process temperature so that cooling would be required. The potential advantage of operating at a higher temperature is the greater cooling gradient. In the base case, cooling water is available at 10°C, so that a cooling gradient of 60°C for Sulfolobus can be compared with only 30°C for T. ferrooxidans. Thus a for thermophilic system, cost savings for a smaller cooling system would be realized both for capital (cooling tower, pumps, piping, electrical, instrumentation) and operating (power). Table 21 gives the costs of cooling for the base case.

As the cooling water temperature increases, the capital and operating costs rise significantly for the mesophilic system (Figures 12 and 13). For 30°C cooling water, costs are more than double than those of the thermophilic system. However, as the data in Table 22 show, the difference in costs, expressed as a percentage of overall plant costs, are small at 1.6% of capital and 0.8% of operating. Elimination of the cooling tower, included in this example but not always needed, would drastically reduce these percentage differentials. Therefore, reduced cooling offers only minor potential for improved economics, although cooling at higher process temperatures may be critically advantageous in tropical or hot-arid climates where cooling water availability is limited and/or >30°C.

5.3 Kinetics Considerations

Improved oxidation kinetics, resulting in reduced pulp residence time in the bioleach tanks, would reduce both capital (tanks, concrete, agitators, piping, instrumentation, electrical) and operating (power) costs of the bioleach section of the plant. Table 23 gives the costs of

the bioleach section of the plant (base case) and Figures 14 and 15 show the impact of reduced retention time on capital and operating costs. In the case of kinetic improvements, the savings in costs could be significant (Table 24). For example, reducing the residence time to 30 h from the base case of 60 h would result in overall plant cost savings of 4.1% of capital and 2.1% of operating.

However, to realize such savings, the Sulfolobus system must be able to operate at comparable leach pulp densities to the T. ferrooxidans system. If not, potential cost savings due to faster kinetics are rapidly eroded by the increased cost of operating at lower pulp density. This relationship between cost, residence time and pulp density is shown for capital and operating costs in Figures 16 and 17.

It should be noted that a significant reduction in residence time due to improved kinetics could result in increased costs of both cooling and aeration due to the need to provide specialized cooling and aeration systems.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The study of the thermophile Sulfolobus for mineral leaching applications is a relatively new field. However, despite some uncertainty in nomenclature and apparent differences in oxidative capability, a review of the literature shows that the organism clearly has utility and some workers have achieved significant experimental progress. Little work has been done to apply Sulfolobus to the treatment of refractory gold ores and concentrates. The ability of the organism to achieve rapid oxidation of gold-bearing minerals such as pyrite has been claimed but considerable work is required to demonstrate that a thermophilic system is a viable alternative to the extensively studied mesophilic system using T. ferrooxidans under practical operating constraints.

The results of the laboratory study did not show Sulfolobus to be a superior leaching organism to T. ferrooxidans. Four concentrates and two ores were evaluated but none provided iron leach rates or extractions as good as the mesophile. Further work is required to gain more experience in the use of Sulfolobus for the oxidation of refractory materials and to demonstrate fast oxidation kinetics at practical pulp densities. In addition, significant improvements in gold metallurgy following pretreatment by Sulfolobus has to be demonstrated.

An economic comparison between a thermophilic and a mesophilic oxidation system for the pretreatment of a refractory ore has shown that kinetic improvements postulated for the higher temperature system can save significant capital and operating costs. However, the Sulfolobus-based system must be able to maintain comparable pulp densities to the T. ferrooxidans system to be competitive. Reduced cooling requirements for the

thermophilic system offer only minor potential for improved process economics, except in hot climates where cooling water availability is limited.

The understanding of the role of T. ferrooxidans in the oxidation of sulphide minerals that allowed development of leach systems having immediate commercial potential has taken many years of extensive investigations by many laboratories to attain. This study has been a relatively low-level effort to fast-track the development of a new leach system using a microorganism which has been little studied for mineral leaching, particularly for the application in question. It is our opinion that further work is warranted and we recommend that a further study be carried out to increase experience with working with Sulfolobus and to achieve a higher degree of acclamation of the culture to growth on the refractory ores and concentrates. This would allow verification of the currently theoretical advantages that are put forward for the thermophilic system and indicate the feasibility of developing an alternative biooxidation pretreatment system.

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8.0 REFERENCES

1. Colmer, A.R. and Hinkle, M.E. The role of microorganisms in acid mine drainage: a preliminary report. Science, 106, 253, 1947.
2. Brierley, C.L. Microbiological mining. Sci. Am. 247 (2), 44, 1982.
3. Curtin, M.E. Microbial mining and metal recovery. Corporations take the long and cautious path. Biotechnology, 1, 228, 1983.
4. Kelly, D.P., Norris, P.R., and Brierley, C.L. Microbiological methods for the extraction and recovery of metals. In: Bull, A.T. et al (Eds.), Microbial Technology: Current State, Future Prospects. Proc. 29th Symp. Soc. Gen. Microbiol., Cambridge University Press, Cambridge, 1979, 263-308.
5. Addison, R. Gold and silver extraction from sulphide ores. Mining Congr. J. 66 (10), 1980, 47-54.
6. Lawrence, R.W. and Bruynesteyn, A. Biological preoxidation to enhance gold and silver recovery from refractory pyrite ores and concentrates. CIM Bulletin, 76 (857), 1983, 107-110.
7. Lawrence, R.W. and Gunn, J.D. Biological preoxidation of a pyritic gold concentrate. In: Frontier Technology in Mineral Processing, Spisak, J.F. and Jurgenson, G.V. (Eds.), AIME, New York, 1985, 13-17.
8. Lawrence, R.W. Biological preoxidation leaching for refractory gold and silver. Proc. 17th Canadian Mineral Processors Congress, Ottawa, 1985, 13-17.
9. Bruynesteyn, A. and Hackl, R.P. The Biotankleach Process for the treatment of gold/silver ores. In: Microbiological Effects on Metallurgical Processes, Clum, J.A. and Haas, L.A. (Eds.), Met. Soc. AIME, Pennsylvania, 1985, 121-127.
10. Karavaiko, G.I., Chuchalin, L.K., Pivovarova, T.A., Yemel'yanov, B.A. and Dorofeyev, A.G. Microbiological leaching of metals from arsenopyrite containing concentrates. In: Fundamental and Applied Biohydrometallurgy, R.W. Lawrence, R.M.R. Branion and H.G. Ebner (Eds.), Elsevier, Amsterdam, 1986, 115-126.
11. Livesey-Goldblatt, E. Bacterial leaching of gold, uranium, pyrite-bearing compacted mine tailing slimes. In: Fundamental and Applied Biohydrometallurgy, R.W. Lawrence, R.M.R. Branion and H.G. Ebner (Eds.), Elsevier, Amsterdam, 1986, 89-96.
12. Marchant, P.B. and Lawrence, R.W. Flowsheet design, process control and operating strategies in the biooxidation of refractory gold ores. 25th Conf. Metallurgists, CIM, Toronto, August, 1986.
13. Livesey-Goldblatt, E. Norman, P. and Livesey-Goldblatt, O.R. Gold recovery from arsenopyrite/pyrite ore by bacterial leaching and cyanidation. In: Recent

Progress in Biohydrometallurgy, G. Rossi and A.E. Torma (Eds.),
14. Renner, C.W., Errington, M.T., King, D.J. and Pooley, F.D. Economics of bacterial leaching. 23rd Conf. Metallurgists, CIM, Quebec, August, 1984.
15. Marchant, P.B. Commercial piloting and the economic feasibility of plant scale continuous biological tank leaching at Equity Silver Mines Limited. In: Fundamental and Applied Biohydrometallurgy, R.W. Lawrence, R.M.R. Branion and H.G. Ebner (Eds.), Elsevier, Amsterdam, 1986,
16. Wiegel, J. and Ljungdahl, L.G. The importance of thermophilic bacteria in biotechnology. Crit. Rev. Microbiol. 3 (1), 1986, 39-108.
17. Norris, P.R., Parrott, L.M. and Marsh, R.M. Moderately thermophilic mineral-oxidizing bacteria. In: Biotechnology for the Mining, Metal-Refining, and Fossil Fuel Processing Industries, Biotechnology and Bioengineering Symposium No. 16, H.L. Ehrlich and D.S. Holmes (Eds.), John Wiley & Sons, New York, 1986, 253-262.
18. Brierley, C.L. Thermophilic microorganisms in extraction of metals from ores. Develop. Industrial Microbiol., 18, 1977, 273-284.
19. Brierley, C.L., Brierley, J.A., Norris, P.R. and Kelly, D.P. Metal-tolerant microorganisms of hot, acid environments. In: Microbial Growth and Survival in Extremes of Environment. Gould, G.W. and Corry, J.E.L. (Eds.), Academic Press, London, 1980.
20. Chakraborti, N. and Murr, L.E. Kinetics of leaching chalcopyrite-bearing waste rock with thermophilic and mesophilic bacteria. Hydromet. 5, 1980, 337-354.
21. Brierley, J.A. Facultative-thermophilic Thiobacillus-like bacteria in metal leaching. In: Biogeochemistry of Ancient and Modern Environments, Trudinger, P.A. et al (Eds.) Australian Academy of Sciences, Canberra, 1980, 445-450.
22. Brock, T.D., Brock, K.M., Belly, R.T. and Weiss, R.L. Sulfolobus: a new genus of sulfur-oxidizing bacteria living at low pH and high temperature. Arch. Mikrobiol. 84, 1972, 54-68.
23. Brock, T.D., Cook, S., Petersen, S. and Mosser, J.L. Biogeochemistry and bacteriology of ferrous iron oxidation in geothermal habitats. Geochimica et Cosmochima Acta, 40, 1976, 493-500.
24. Brierley, C.L. and Brierley, J.A. A chemoautotrophic and thermophilic microorganism isolated from an acid hot spring. Can. J. Microbiol. 19, 1973, 183-188.
25. Brock, T.D. Thermophilic Microorganisms and Life at High Temperature. Springer-Verlag, New York, 1978.
26. Marsh, R.M. and Norris, P.R. The isolation of some thermophilic, autotrophic, iron- and sulphur-oxidizing bacteria. FEMS Microbiol. Lett. 17, 1983, 311-315.

27. Brierley, C.L. and Murr, L.E. Leaching: use of a thermophilic and chemoautotrophic microbe. Science, 179, 1973,488-490.
28. Brierley, C.L. Leaching,: use of a high-temperature microbe. Proc. Solution Mining Symp., Aplan, F.F., McKinney, W.A. and Pernichele, A.D. (Eds.), 1974, 461-469.
29. Brierley, J.A. and Lockwood, S.J. The occurrence of thermophilic iron-oxidizing bacteria in a copper leaching system. FEMS Microbiol. Lett. 2, 1977, 163-165.
30. Brierley, J.A. and Brierley, C.L. Microbial leaching of copper at ambient and elevated temperatures. In: Metallurgical Applications of Bacterial Leaching and Related Microbiological Phenomena. L.E. Murr, A.E. Torma and J.A. Brierley (Eds.), Academic Press, New York, 1978, 477-490.
31. Murr, L.E. and Berry, V.K. Observations of a natural thermophilic microorganism in the leaching of a large experimental, copper-bearing waste body. Metall. Trans. (B), 10, 1979, 523-531.
32. Brierley, C.L. Leaching of chalcopyrite ore using Sulfolobus species. Devel. Indust. Microbiol. 21, 1980, 435-444.
33. Madsen, B.W. and Groves, R.D. Percolation leaching of a chalcopyrite-bearing ore at ambient and elevated temperatures with bacteria. USBM R.I. 8827, 1983, 18pp.
34. Brierley, C.L. Molybdenite-leaching: use of a high temperature microbe. J. Less Common Metals, 36, 1974, 237-247.
35. Marsh, R.M., Norris, P.R. and Le Roux, N.W. Growth and mineral oxidation studies with Sulfolobus. In: Recent Progress in Biohydrometallurgy, G. Rossi and A.E. Torma (Eds.), Assoc. Mineraria Sarda, 09016 Iglesias, Italy, 1983, 71-81.
36. Norris, P.R. and Parrott, L. High temperature, mineral concentrate dissolution with Sulfolobus. In: Fundamental and Applied Biohydrometallurgy, R.W. Lawrence, R.M.R. Branion and H.G. Ebner (Eds.), Elsevier, Amsterdam, 1986, 53-76.
37. Groudeva, V.I., Groudev, S.N. and Markov, K.I. A comparison between mesophilic and thermophilic bacteria with respect to their ability to leach sulphide minerals. In: Fundamental and Applied Biohydrometallurgy, R.W. Lawrence, R.M.R. Branion and H.G. Ebner (Eds.), Elsevier, Amsterdam, 1986, 484-485.
38. Kargi, F. and Robinson, J.M. Removal of sulphur from coal by the thermophilic organism Sulfolobus acidocaldarius. Appl. Environ. Microbiol. 44 (4), 1982, 878-883.
39. Kargi, F. and Robinson, J.M. Biological removal of pyritic sulphur from coal by the thermophilic organism

Sulfolobus acidocaldarius. Biotech. Bioeng. 27, 1985, 41-49.

40. Hutchins, S.R, Brierley, J.A. and Brierley, C.L. Microbial pretreatment of carbonaceous gold ores. 116th Annual Meeting AIME, Denver, Feb 23-27, 1987.

41. Weiss, R.L. Subunit cell wall of Sulfolobus acidocaldarius. J. Bacteriol. 118, 1974, 275-284.

TABLES

Table 1

ORE/CONCENTRATE HEAD ASSAYS

SAMPLE	Au g/t	Ag g/t	Fe %	As %	S %
CIN	19.6	29.5	10.3	0.1	10.4
NN	23.2	222.5	36.3	0.8	42.6
MET	26.0	35.0	40.0	12.0	41.0
CP	98.7	34.9	32.4	11.0	30.6
NAM	31.3	40.3	4.1	0.1	4.4
RD	7.2	59.0	9.5	0.1	11.1

Table 2

COMPARISON OF TYPICAL LEACH RESULTS
SULFOLOBUS vs T.FERROOXIDANS

CONCENTRATE /ORE	SULFOLOBUS PD (%)	SULFOLOBUS Fe Ext (%)	SULFOLOBUS Time (days)	T.FERROOXIDANS PD (%)	T.FERROOXIDANS Fe Ext (%)	T.FERROOXIDANS Time (days)
CIN	5	30	14	5	68	9
	10	25	14	10	60	7
	20	24	16	20	67	14
NN	5	27	28	5	77	17
	10	30	20	10	77	17
	20	25	20	20	35	17
	30	34	37			
MET	5	8	13			
	10	5	13	10	95	8
	20	4	17			
CP	5	23	9			
	10	31	52	10	95	7
NAM	5	36	9			
	10	57	20			
	15	52	27	20	90	4
	20	40	20	30	90	6
RD	6	46	52	26	54	3
					76	5

Table 3

IRON PRECIPITATION TEST
(at 65C)

(Fe values in ppm)

TIME (h)	Ferric pH 1.9	Ferric pH 1.2	Ferric Salts/pH 1.9	Ferric Salts/pH 1.2
0	8250	8250	7700	7350
25	7450	7170	6510	7075
50	7200	7200	4980	6600
96	7000	7280	3920	5680
TIME (h)	**Ferrous pH 1.9**	**Ferrous pH 1.2**	**Ferrous Salts/pH 1.9**	**Ferrous Salts/pH 1.2**
0	8750	9400	8750	10150
25	8210	9530	8775	10895
50	8100	8900	6360	9400
96	7960	6540	5280	7500

Note: Tests conducted using either ferric or ferrous iron solutions at the strength shown, with and without the standard addition of nutrient salts. Sulphuric acid used to set the initial pH values.

Table 4

SULFOLOBUS LEACHES OF NN CONCENTRATE
EFFECT OF INITIAL pH

Time (hours)	Initial pH 3.0 pH	Eh (mV)	Fe(S) (g/L)	Initial pH 2.5 pH	Eh (mV)	Fe(S) (g/L)
0.0	3.02	335	0.96	2.46	356	0.96
48.0	2.23	358	0.89	2.17	359	0.95
123.0	1.84	364	1.23	1.82	367	1.43
171.0	1.75	368	1.55	1.72	369	1.65
219.5	1.61	378	1.95	1.60	380	2.07
288.5	1.53	413	2.25	1.53	415	2.20
336.5	1.42	367	2.51	1.44	368	2.66
384.0	1.47	379	2.89	1.50	380	2.70
479.5	1.39	399	3.46	1.43	397	3.30
552.0	1.35	400	4.05	1.28	398	3.55
675.0	1.23	411	4.48	1.26	410	4.15

Time (hours)	Initial pH 2.0 pH	Eh (mV)	Fe(S) (g/L)	Initial pH 1.6 pH	Eh (mV)	Fe(S) (g/L)
0.0	2.00	370	1.26	1.59	375	1.14
48.0	1.92	369	1.26	1.58	373	1.50
123.0	1.61	373	2.06	1.36	377	2.15
171.0	1.53	378	2.42	1.31	382	2.42
219.5	1.46	388	2.75	1.28	388	2.82
288.5	1.39	418	3.06	1.23	416	3.32
336.5	1.27	375	3.47	1.12	372	3.51
384.0	1.36	388	3.78	1.18	388	3.86
479.5	1.29	402	4.30	1.13	402	4.25
552.0	1.14	403	4.60	1.00	404	5.00
675.0	1.16	415	5.05	1.05	415	5.40

Table 5

SULFOLOBUS LEACHES OF NAM ORE
N/P AND N/Mg RATIOS

Test #	N/P	N/Mg	$(NH_4)_2SO_4$ (g/L)	K_2HPO_4 (g/L)	$MgSO_4$ (g/L)
1	12.5	31.8	2.10	0.18	0.18
2	50.0	15.0	11.69	0.25	2.13
3	50.0	30.0	11.69	0.25	1.06
4	30.0	40.0	7.01	0.25	0.48
5	30.0	15.0	7.01	0.25	1.28
6	15.0	30.0	3.51	0.25	0.32
7	15.0	7.5	3.51	0.25	1.28
8	8.0	20.0	1.87	0.25	0.26
9	8.0	4.0	1.87	0.25	1.28
10	6.4	16.4	3.00	0.50	0.50

Table 6

SULFOLOBUS LEACHES OF CIN CONCENTRATE
EFFECT OF PULP DENSITY

Time (hours)	2% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)	5% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0.0	1.64	405	0.52	0.50	1.62	390	0.59	0.65
24.0	1.68	318	0.55	0.58	1.65	319	0.68	0.78
48.5	1.66	321	0.59	0.50	1.62	322	0.83	0.88
120.0	1.67	328	0.60	0.63	1.66	321	1.03	0.98
169.0	1.62	424	0.65	0.70	1.59	423	1.08	1.08
216.0	1.65	427	0.65	0.75	1.58	428	1.13	1.48
291.5	1.69	387	0.88	0.88	1.59	384	1.43	1.80
339.5	1.67	407	1.00	0.83	1.55	402	1.55	1.95
365.0	1.56	390	0.76	0.86	1.41	386	1.38	1.98
388.5	1.64	380	0.70	0.95	1.53	372	1.35	2.00

Time (hours)	10% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)	15% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0.0	1.64	376	0.70	0.78	1.63	372	0.83	0.98
24.0	1.69	318	0.88	0.98	1.67	318	1.05	1.28
48.5	1.65	322	1.13	1.00	1.61	323	1.38	1.38
120.0	1.64	322	1.45	1.33	1.58	324	1.80	1.78
169.0	1.56	422	1.68	1.73	1.51	423	2.30	2.40
216.0	1.52	426	1.90	2.15	1.46	428	2.95	3.13
291.5	1.52	383	2.03	2.65	1.45	384	2.78	3.25
339.5	1.48	400	2.60	3.15	1.40	399	2.75	3.50
365.0	1.34	384	2.55	3.08	1.24	385	3.50	3.76
388.5	1.44	369	2.25	3.00	1.35	369	3.80	4.60

Time (hours)	20% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0.0	1.62	366	0.96	1.18
24.0	1.65	321	1.20	1.48
48.5	1.61	324	1.55	1.65
120.0	1.55	326	2.23	2.43
169.0	1.46	425	2.80	2.88
216.0	1.40	428	3.48	3.58
291.5	1.41	388	3.68	4.15
339.5	1.37	400	3.55	4.60
365.0	1.19	384	4.24	4.93
388.5	1.27	368	5.00	5.90

Table 7

T.FERROOXIDANS LEACHES OF CIN CONCENTRATE
EFFECT OF PULP DENSITY

Time (hours)	2% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)	5% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0.0	1.70	383	0.45	0.48	1.67	361	0.49	0.55
24.0	1.69	408	0.53	0.50	1.67	383	0.60	0.58
48.5	1.60	565	1.35	1.20	1.53	526	1.70	1.65
120.0	1.56	665	0.43	1.55	1.41	692	2.83	3.28
169.0	1.59	593	1.23	2.15	1.40	611	3.13	3.73
216.0	1.59	620	1.03	1.40	1.43	642	3.50	3.20
291.5	1.57	609	1.01	1.10	1.39	632	3.25	2.70
339.5	1.55	605	1.30		1.35	613	2.85	
365.0	1.60	610	1.50		1.42	624	2.80	
388.5								

Time (hours)	10% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)	15% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0.0	1.69	349	0.63	0.78	1.68	345	0.70	0.90
24.0	1.68	365	0.73	0.90	1.66	355	0.90	1.00
48.5	1.57	464	1.50	1.30	1.57	439	1.10	1.23
120.0	1.35	620	4.10	4.20	1.35	492	3.75	3.85
169.0	1.24	620	5.80	5.50	1.17	570	7.25	8.25
216.0	1.26	651	6.20	5.35	1.18	657	7.95	10.45
291.5	1.21	647	5.45	5.40	1.09	660	6.86	9.40
339.5	1.16	632	5.37		1.00	643	8.60	
365.0	1.21	638	4.65		1.08	648	7.00	
388.5								

Time (hours)	20% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0.0	1.68	345	0.78	1.13
24.0	1.66	351	1.05	1.15
48.5	1.56	409	1.60	1.30
120.0	1.39	563	3.28	3.40
169.0	1.17	574	5.50	5.75
216.0	1.14	633	9.25	8.85
291.5	1.01	662	12.28	10.80
339.5	0.91	649	13.76	11.20
365.0	0.97	650	11.60	11.80
388.5				

Table 8

SULFOLOBUS LEACHES OF BH CONCENTRATE
EFFECT OF PULP DENSITY
(1st Series)

Time	2% PD			5% PD			8% PD			12% PD		
(hours)	pH	Eh (mV)	Fe(S) (g/L)	pH	Eh (mV)	Fe(S) (g/L)	pH	Eh (mV)	Fe(S) (g/L)	pH	Eh (mV)	Fe(S) (g/L)
0.0	2.02	392	5.80	2.00	370	1.26	1.98	362	1.72	2.00	351	2.32
48.0	2.00	374	6.05	1.92	369	1.26	1.93	364	1.80	1.93	363	2.44
123.0	1.77	374	9.00	1.61	373	2.06	1.56	372	2.74	1.54	369	3.46
171.0	1.71	379	10.60	1.54	378	2.42	1.45	376	3.30	1.44	375	4.05
219.5	1.66	385	12.60	1.46	388	2.75	1.37	386	3.85	1.35	386	4.92
288.5	1.58	420	14.50	1.39	418	3.06	1.34	420	4.55	1.29	422	5.74
336.5	1.53	374	15.00	1.27	375	3.47	1.16	372	5.35	1.13	374	6.56
384.0	1.50	387	17.20	1.28	388	3.90	1.12	386	5.44	1.09	390	6.80
479.5	1.48	401	20.00	1.29	402	4.30	1.08	401	5.66	1.06	403	8.80
552.0	1.35	403	21.50	1.14	403	4.60	0.93	408	6.50	0.85	407	9.00
675.0	1.40	415	25.00	1.16	415	5.05	0.99	420	8.50	0.90	419	10.75
827.0	1.37	419	28.50				0.92	422	9.40	0.82	417	13.01
1044.5	1.27	351	33.70				0.76	355	11.90	0.63	355	15.40

Time	16% PD			20% PD			25% PD		
(hours)	pH	Eh (mV)	Fe(S) (g/L)	pH	Eh (mV)	Fe(S) (g/L)	pH	Eh (mV)	Fe(S) (g/L)
0.0	2.00	347	3.28	2.00	340	4.00	1.98	340	4.70
48.0	1.89	359	3.42	1.86	356	4.72	1.83	354	5.30
123.0	1.45	368	4.87	1.40	370	6.08	1.39	366	6.64
171.0	1.37	376	5.43	1.29	378	7.00	1.24	375	8.10
219.5	1.28	385	7.00	1.20	388	8.50	1.17	386	9.20
288.5	1.23	424	8.50	1.15	420	10.10	1.10	421	11.20
336.5	1.07	375	8.70	0.96	379	10.40	0.92	376	12.00
384.0	1.04	391	9.20	0.95	392	11.40	0.90	393	13.45
479.5	1.02	402	10.40	0.94	401	12.00	0.86	401	15.00
552.0	0.79	406	10.75	0.69	407	13.50	0.63	403	15.75
675.0	0.85	419	12.75	0.75	419	16.50	0.67	418	19.75
827.0	0.82	418	13.90	0.63	415	21.00	0.55	410	24.20
1044.5	0.68	368	16.50	0.49	354	24.50	0.38	350	28.00

Table 9

T.FERROOXIDANS LEACHES OF NN CONCENTRATE
EFFECT OF PULP DENSITY

TIME (hours)	5% PD pH	Eh (mV)	Fe(S) (g/L)	10% PD pH	Eh (mV)	Fe(S) (g/L)
0	1.66	441	0.76	1.61	425	0.65
72	1.56	426	1.16	1.51	388	1.08
168	1.14	504	4.87	1.12	470	4.70
264	0.79	589	11.50	0.77	557	11.00
408	0.86	628	14.00	0.69	576	28.00
552	0.78	640	13.00	0.54	620	29.00

TIME (hours)	15% PD pH	Eh (mV)	Fe(S) (g/L)	20% PD pH	Eh (mV)	Fe(S) (g/L)
0	1.59	414	0.73	1.65	317	0.52
72	1.54	375	1.20	1.59	341	0.69
168	1.21	448	4.50	1.44	495	2.75
264	0.77	544	10.00	0.95	519	10.00
408	0.68	551	24.00	0.62	530	18.80
552	0.55	560	22.00	0.57	541	25.00

Table 10

SULFOLOBUS LEACHES OF NN CONCENTRATE
EFFECT OF PULP DENSITY
(2nd Series)

TIME (hours)	5% PD pH	Eh (mV)	Fe(S) (g/L)	10% PD pH	Eh (mV)	Fe(S) (g/L)
0.0	1.43	404	0.75	1.39	398	1.50
73.5	1.42	399	1.28	1.39	398	1.85
149.0	1.31	322	2.06	0.94	320	3.08
216.0	1.21	326	2.49	1.05	325	3.90
336.5	1.14	318	3.25	0.98	318	5.43
412.0	0.99	326	3.66	0.81	323	6.35
486.0	0.90	301	4.00	0.79	299	7.05
582.0	1.10	343	4.25	0.90	340	8.60
671.0	1.00	426	5.75	0.82	410	8.50
743.0	0.98	355	5.00	0.83	356	8.50

TIME (hours)	15% PD pH	Eh (mV)	Fe(S) (g/L)	20% PD pH	Eh (mV)	Fe(S) (g/L)
0.0	1.34	394	1.85	1.30	391	2.15
73.5	1.28	395	2.98	1.26	399	3.40
149.0	0.95	320	4.08	0.96	320	4.70
216.0	0.92	320	5.88	0.90	321	6.60
336.5	0.82	317	7.72	0.79	318	8.40
412.0	0.71	323	9.50	0.58	323	10.80
486.0	0.65	300	11.00	0.60	301	12.10
582.0	0.79	340	12.60	0.73	341	14.20
671.0	0.73	423	15.00	0.68	418	15.50
743.0	0.70	350	13.00	0.60	350	15.00

Table 11

SULFOLOBUS LEACHES OF CP CONCENTRATE

Time (days)	5% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)	pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0	1.62	423	1.73		1.58	417	2.33	
3	1.92	380	2.30		1.79	384	2.75	
6	1.94	310	2.78		1.80	315	3.24	
9	1.86	310	3.23		1.81	320	3.67	
14	1.94	328	2.69		1.78	340	3.06	
17	1.72	338	2.70		1.60	349	2.80	
21	1.97	340	2.44		1.69	326	2.85	
24	1.88	342	2.59		1.63	363	2.75	
28	1.80	373	2.25	3.05	1.58	390	2.60	2.85
31	1.88	367	2.15	2.70	1.64	391	2.30	3.20

Time (days)	10% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0	1.62	416	1.90	
3	1.84	372	2.48	
6	1.88	306	3.25	
9	1.79	305	3.67	
14	1.91	306	4.44	
17	1.86	312	4.56	
21	1.98	303	4.24	
24	1.87	340	3.45	
28	1.79	366	2.45	3.04
31	1.94	362	2.25	3.40

Table 12

SULFOLOBUS LEACHES OF MET CONCENTRATE
EFFECT OF PULP DENSITY

TIME (days)	2% PD pH	2% PD Eh (mV)	2% PD Fe(S) (g/L)	5% PD pH	5% PD Eh (mV)	5% PD Fe(S) (g/L)	10% PD pH	10% PD Eh (mV)	10% PD Fe(S) (g/L)
0	1.65	393	0.30	1.57	396	0.53	1.52	402	0.59
9	1.76	346	0.62	1.76	336	1.47	1.87	326	2.09
13	1.73	380	0.53	1.71	363	1.59	1.76	354	2.05
17	1.48	389	0.48	1.47	374	1.46	1.48	367	2.03

TIME (days)	15% PD pH	15% PD Eh (mV)	15% PD Fe(S) (g/L)	20% PD pH	20% PD Eh (mV)	20% PD Fe(S) (g/L)
0	1.50	395	0.58	1.63	399	0.48
9	1.87	324	2.43	2.16	313	3.03
13	1.73	353	2.71	1.98	344	3.10
17	1.46	360	2.91	1.50	357	3.58

Table 13

SULFOLOBUS LEACHES OF NAM ORE
EFFECT OF PULP DENSITY
(1st Series)

TIME (days)	5% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)	10% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0	1.75	378	0.34		1.60	372	0.61	
3	1.78	376	0.41		1.62	379	0.86	
5	1.75	378	0.56	1.08	1.57	378	1.01	1.60
7	1.72	386	0.56		1.57	387	1.16	
10	1.69	387	0.66		1.51	388	1.66	
12	1.66	399	0.74	1.15	1.47	398	1.53	1.80
14	1.63	394	0.83		1.47	395	1.59	
17	1.63	415	0.87		1.44	415	1.61	
19	1.61	418	0.96		1.40	419	1.78	2.00
21	1.59	413	0.91		1.42	414	1.86	
25	1.65	412	0.86	1.20	1.43	413	1.91	2.25

TIME (days)	15% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)	20% PD pH	Eh (mV)	Fe(S) (g/L)	Fe(T) (g/L)
0	1.72	374	0.91		1.75	370	1.02	
3	1.75	377	1.46		1.77	375	1.51	
5	1.65	376	1.61	2.42	1.67	378	1.81	2.75
7	1.65	384	1.91		1.66	385	2.16	
10	1.59	387	1.99		1.58	385	2.41	
12	1.55	398	2.31	2.55	1.55	397	2.96	3.27
14	1.52	397	2.46		1.52	395	3.16	
17	1.48	414	2.56		1.46	414	2.81	
19	1.42	421	2.31		1.43	419	3.06	
21	1.40	416	2.76		1.41	413	3.21	
25	1.44	415	2.73	3.05	1.42	412	3.51	3.55

Table 14

SULFOLOBUS LEACHES OF NAM ORE
EFFECT OF PULP DENSITY
(2nd Series)

TIME (days)	5% PD pH	Eh (mV)	Fe(S) (g/L)	10% PD pH	Eh (mV)	Fe(S) (g/L)
0	1.68	385	0.29	1.71	377	0.49
2	1.60	371	0.39	1.59	365	0.99
6	1.59	374	0.54	1.56	370	1.34
9	1.54	376	0.74	1.49	375	1.61
13	1.56	383	0.64	1.45	380	1.81
16	1.55	376	0.64	1.43	377	2.14
20	1.57	379	0.64	1.41	383	2.34
23	1.54	387	0.59	1.39	390	1.94
27	1.59	397	0.59	1.45	400	2.09
30	1.60	394	0.59	1.44	395	1.89
34	1.64	395	0.52	1.49	397	1.89
37	1.66	395	0.42	1.45	403	2.04

TIME (days)	15% PD pH	Eh (mV)	Fe(S) (g/L)	20% PD pH	Eh (mV)	Fe(S) (g/L)
0	1.73	378	0.69	1.80	377	1.19
2	1.63	364	1.19	1.68	366	1.64
6	1.58	367	1.79	1.59	370	2.34
9	1.48	371	2.14	1.49	375	2.44
13	1.45	377	2.52	1.46	382	2.89
16	1.40	374	3.24	1.41	375	3.29
20	1.37	381	3.19	1.38	384	3.34
23	1.33	389	2.74	1.34	392	3.19
27	1.37	399	3.24	1.39	402	3.34
30	1.36	397	2.99	1.34	401	3.29
34	1.41	402	2.89	1.40	401	3.12
37	1.37	408	2.84	1.38	409	2.94

Table 15

TANK LEACHING OF NN CONCENTRATE WITH SULFOLOBUS
EFFECT OF CARBON DIOXIDE

Time (h)	TANK 1 pH	Eh (mV)	Fe(S) (g/L)	TANK 2 pH	Eh (mV)	Fe(S) (g/L)
		air			air + 5% CO2	
0.0	1.65	406	1.23	1.67	403	1.15
23.5	1.58	388	1.50	1.61	379	1.47
45.5	1.54	381	1.80	1.56	378	1.85
69.5	1.50	386	2.55	1.49	385	2.60
144.0	1.38	391	4.70	1.33	392	4.30
167.5	1.29	390	5.65	1.28	393	4.45
191.0	1.15	392	6.40	1.21	394	4.80
239.0	1.09	396	6.80	1.17	402	4.90
240.0	solution exchange					
242.5	1.38	394	3.35			
298.5	1.25	420	4.40	1.09	427	5.58
333.0	1.20	429	4.95	1.12	445	5.70
381.5	1.12	428	5.40	1.10	449	6.34
477.0	1.05	433	7.10	1.11	454	5.80
525.0	0.98	400	7.80	1.01	418	6.50
526.0				air + 1.5% CO2		
573.0	0.90	399	9.00	0.95	417	7.00
645.5	0.91	403	9.50	0.97	424	7.00
694.5	0.97	412	9.00	0.98	430	8.20
698.0	solution exchange			solution exchange		
698.5	1.37	410	4.55	1.39	418	3.55
717.5	1.30	403	4.70	1.32	420	3.50
741.0	1.10	388	4.90	1.12	408	3.50

Table 16

TANK BIOOXIDATION OF NN CONCENTRATE

I) ASSAYS

PRODUCT	Au (g/t)	Ag (g/t)	Fe (%)	As (%)	S(T) (%)	S(SO4) (%)	Insol. (%)
HEAD	23.20	2225	36.30	0.82	42.60	0.18	18.72
RESIDUE *	37.68	3613	31.00	1.08	31.34	0.51	30.40

* Calculated Au and Ag values

II) SUMMARY

PRODUCT	WT LOSS (%)	S= OXIDN (%)	Fe SOL (%)	As SOL (%)	Au EXTN (%)	Ag EXTN (%)
HEAD	0.0	0.0	0.0	0.0	13.6	16.5
RESIDUE	38.4	55.2	47.4	18.9	39.4	68.4

Table 17

CYANIDATION OF NN CONCENTRATE

I) METALLURGICAL BALANCE

Leach : Direct CN

PRODUCT	WT (g)	ASSAY (g/t) Au	ASSAY (g/t) Ag	DISTRIBN (%) Au	DISTRIBN (%) Ag
SOLN 1h		1.40	134	10.8	10.2
3h		1.70	172	13.2	13.1
5h		1.70	180	13.2	13.7
21h		1.75	208	13.6	15.9
24h	690.6	1.75	216	13.6	16.5
RESIDUE	397.4	19.40	1900	86.4	83.5
CALC HEAD		22.44	2275	100.0	100.0

II) TEST CONDITIONS

SAMPLE (time, h)	pH	[NaCN] (g/L)
0.0	11.1	1.00
1.0	11.0	0.50
3.0	10.9	0.80
5.0	10.7	1.05
21.0	10.4	0.60
24.0	11.0	0.98

Conditions maintained throughout leach:

pH	11.0
[NaCN] (g/L)	1.0
Solids (%)	37

Reagent Consumption:

NaCN (kg/t solids)	3.10
CaO (kg/t solids)	2.82

Table 18

CYANIDATION OF NN CONCENTRATE
BIOOXIDATION RESIDUE

I) METALLURGICAL BALANCE

Leach : Direct CN

PRODUCT	WT (g)	ASSAY (g/t) Au	ASSAY (g/t) Ag	DISTRIBN (%) Au	DISTRIBN (%) Ag
SOLN 24h	854.0	4.00	860	39.4	68.4
RESIDUE	293.0	17.90	1160	60.6	31.6
CALC HEAD		29.56	3667	100.0	100.0

II) TEST CONDITIONS

SAMPLE (time, h)	pH	[NaCN] (g/L)
0.0	11.1	1.00
1.0	11.2	0.50
3.0	11.2	0.83
5.0	11.1	0.83
20.0	10.7	0.83
24.0	10.6	0.99

Conditions maintained throughout leach:

pH	11.0
[NaCN] (g/L)	1.0
Solids (%)	26

Reagent Consumption:

NaCN (kg/t solids)	2.51
CaO (kg/t solids)	2.39

Table 19

350 tpd Processing Plant
Base Case Design Criteria

Feed Rate, tpd	350
Circuit Availability, %	90
Sulphur Content of Ore, %	5
Sulphur Oxidation, %	70
Residence Time, h	60
Pulp Density, % solids	30
Net Heat, kW	2784
Cooling Water Temp, C	10
Mesophilic System Temp, C	40
Thermophilic System Temp, C	70

Table 20

350 tpd Processing Plant
Base Case Costs

PROCESS PLANT :			
	CAPITAL COST	$7,442,000	
	OPERATING COST (Process)	$32.66/t	
	(Labour)	$19.69/t	
BIOLEACHING :			
	CAPITAL COST	$1,270,000	(17.1%)
	OPERATING COST (Process)	$17.83/t	(54.6%)
	(Labour)	$0.99/t	(5.1%)

Table 21

Cooling Costs - Base Case

CAPITAL COSTS	
Cooling Tower Pumps Piping Instrumentation Electrical Materials	$106,780
OPERATING COSTS	
Power	$0.39/t

Table 22

Effect of Cooling Water Temperature
on Capital and Operating Costs

COOLING WATER TEMP	PROCESS WATER TEMP	ΔT	CAPITAL COSTS (000's $)	CAPITAL COSTS (% of Total)	OPERATING COSTS ($/t)	OPERATING COSTS (% of Total)
10 *	40	30	107	1.4	0.39	0.7
15	40	25	119	1.6	0.44	0.8
20	40	20	136	1.8	0.50	1.0
25	40	15	162	2.2	0.59	1.1
30	40	10	207	2.8	0.75	1.4
10	70	60	71	1.0	0.26	0.5
15	70	55	74	1.0	0.27	0.5
20	70	50	79	1.1	0.29	0.6
25	70	45	84	1.1	0.31	0.6
30	70	40	90	1.2	0.33	0.6

* Base Case

Table 23

Biooxidation Plant Costs - Base Case

CAPITAL COSTS	
Tanks Agitators Piping Instrumentation Electrical Materials	$901,680
OPERATING COSTS	
Power (373 kW)	$3.26/t

Table 24

Effect of Residence Time and Pulp Density
on Capital and Operating Costs

RESIDENCE TIME (h)	PULP DENSITY (% Solids)	CAPITAL COSTS (000's $)	CAPITAL COSTS (% of Total)	OPERATING COSTS ($/t)	OPERATING COSTS (% of Total)
60 *	30	902	12.1	3.26	6.2
50	30	808	10.9	2.92	5.6
	25	923	12.4	3.34	6.4
	20	1079	14.5	3.90	7.5
	15	1310	17.6	4.73	9.0
40	30	707	9.5	2.55	4.9
	25	807	10.8	2.92	5.6
	20	944	12.7	3.41	6.5
	15	1146	15.4	4.14	7.9
30	30	595	8.0	2.15	4.1
	25	679	9.1	2.46	4.7
	20	794	10.7	2.87	5.5
	15	964	13.0	3.48	6.7
20	30	466	6.3	1.69	3.2
	25	532	7.2	1.92	3.7
	20	623	8.4	2.25	4.3
	15	756	10.2	2.73	5.2

* Base Case

FIGURES

Fig. 1 Iron precipitation tests

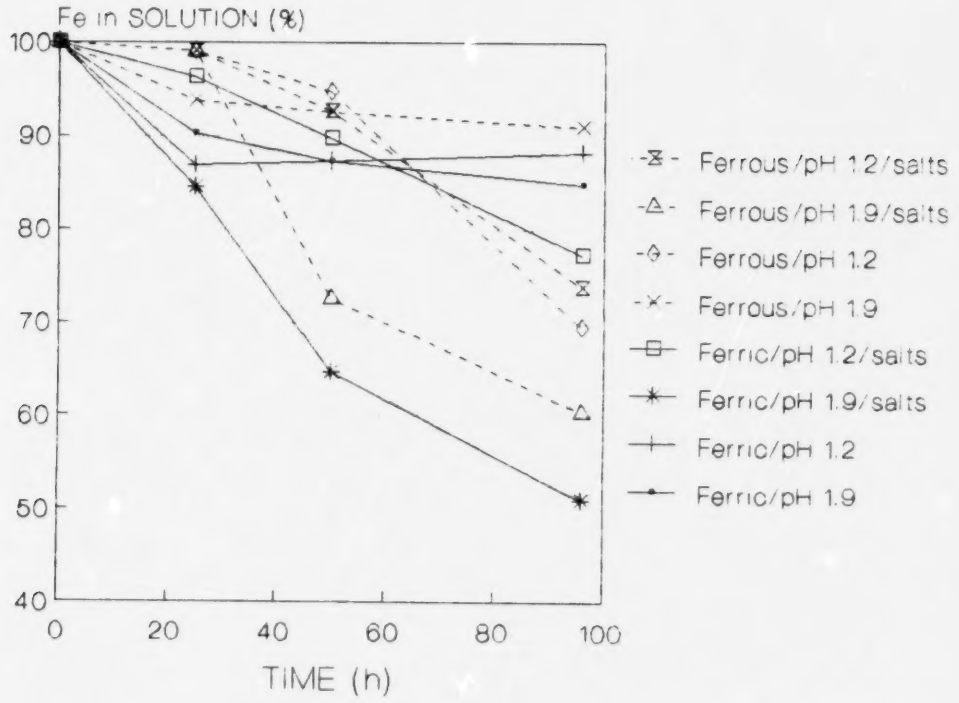

Fig. 2 The effect of agitation on the leaching of concentrates with Sulfolobus

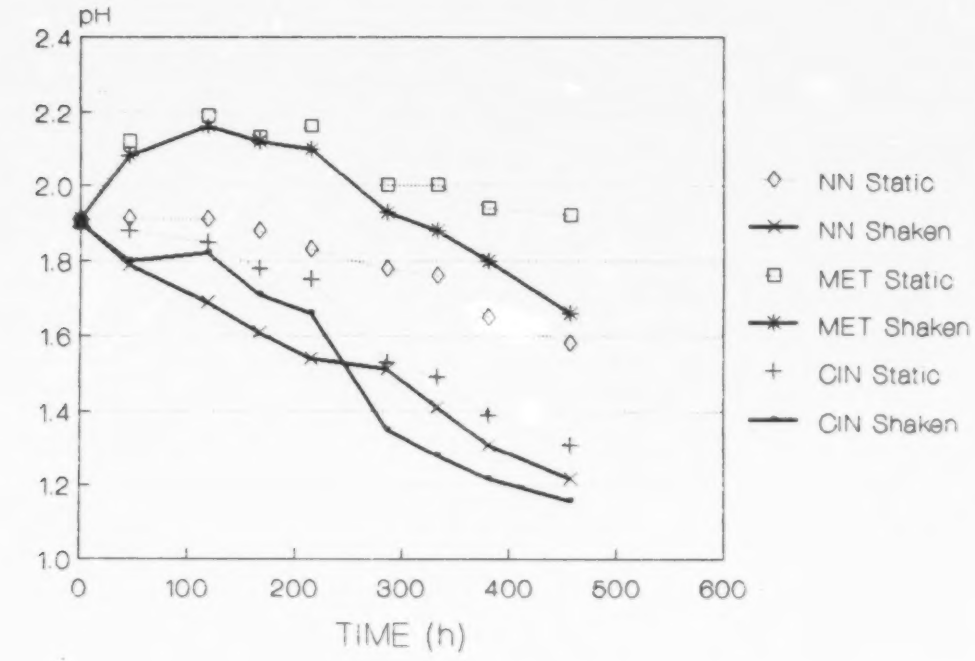

Fig. 3 Leaching of NN concentrate shake flask and agitated tank

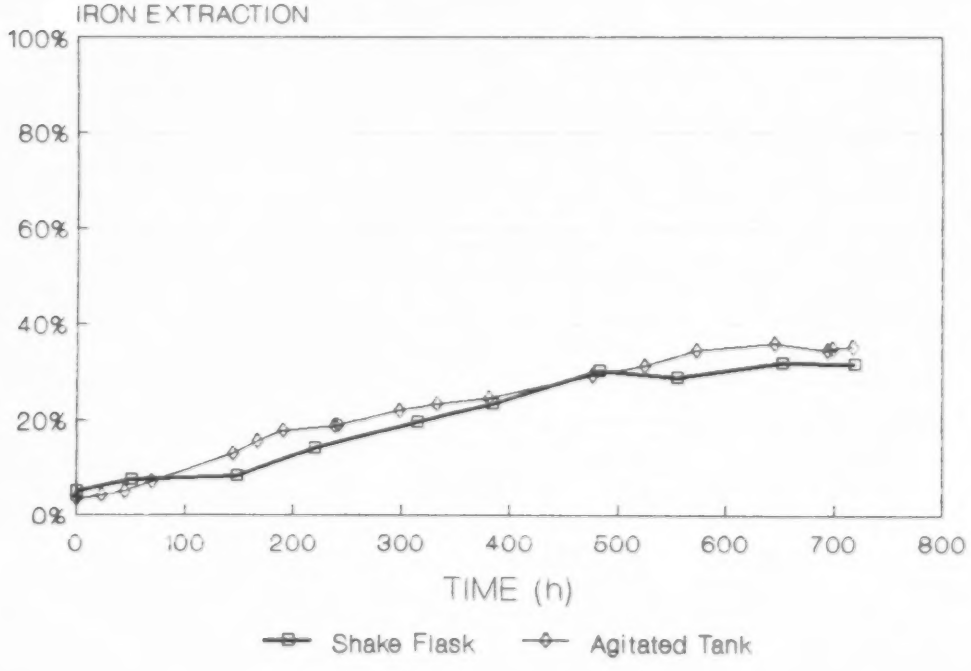

Fig. 4 Effect of pH on leaching of NN concentrate with Sulfolobus

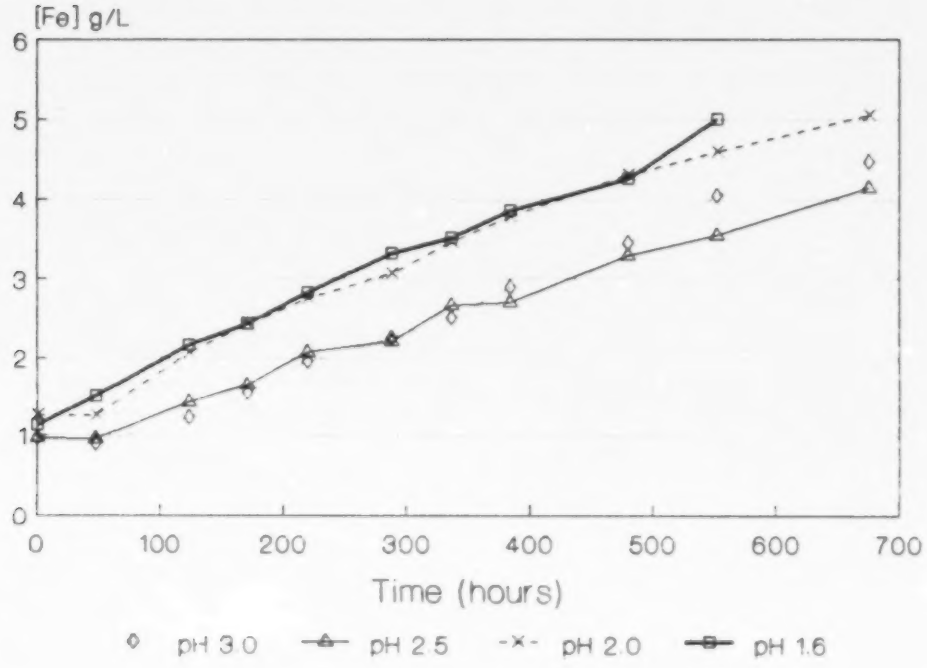

Fig. 5 Effect of pH on leaching of CIN concentrate with Sulfolobus

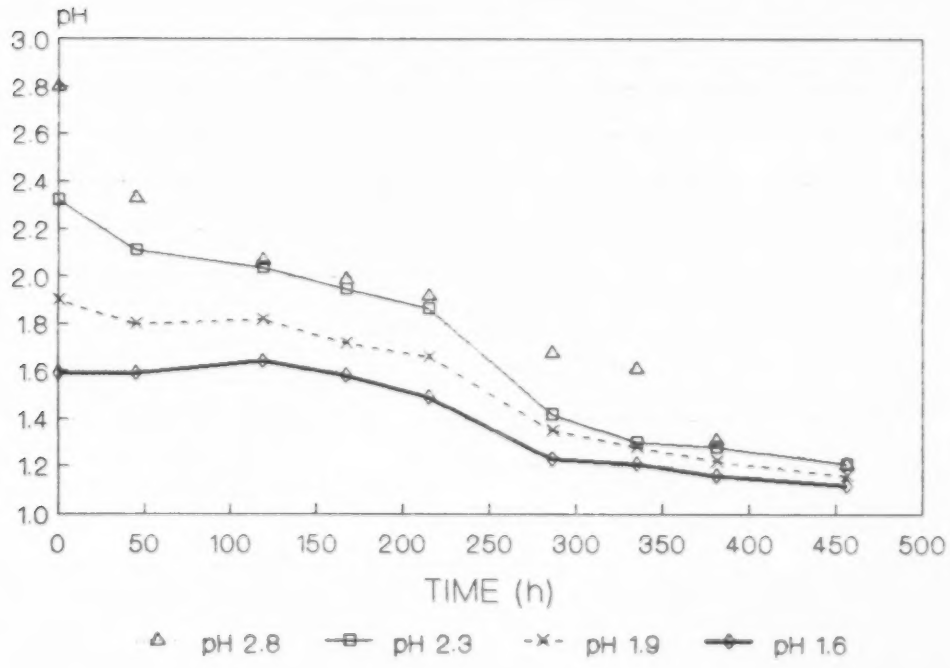

Fig. 6a Leaching NN concentrate with T. ferrooxidans at varying pulp density

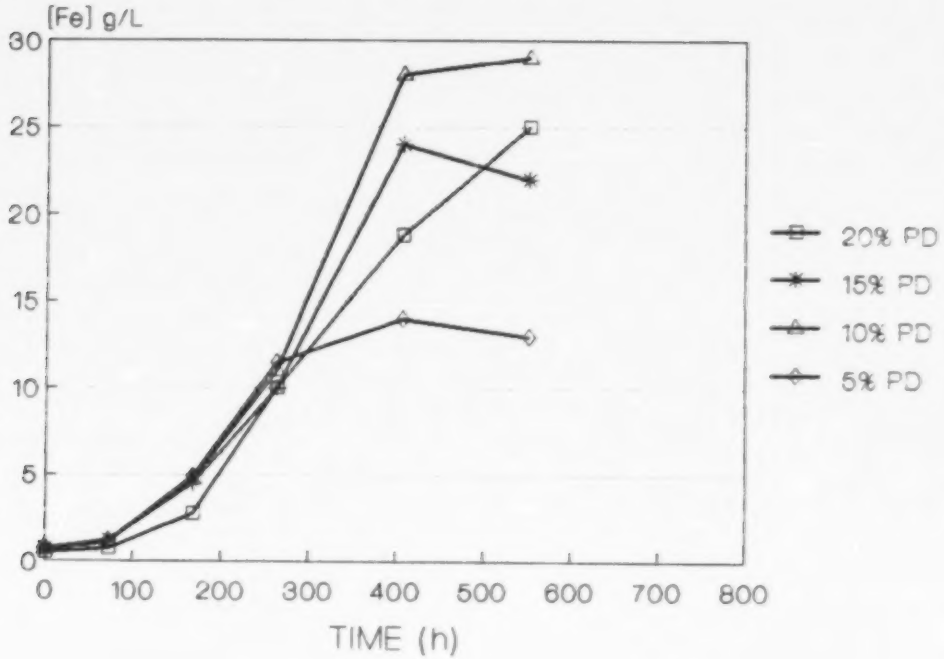

Fig. 6b Leaching of NN concentrate with Sulfolobus at varying pulp density

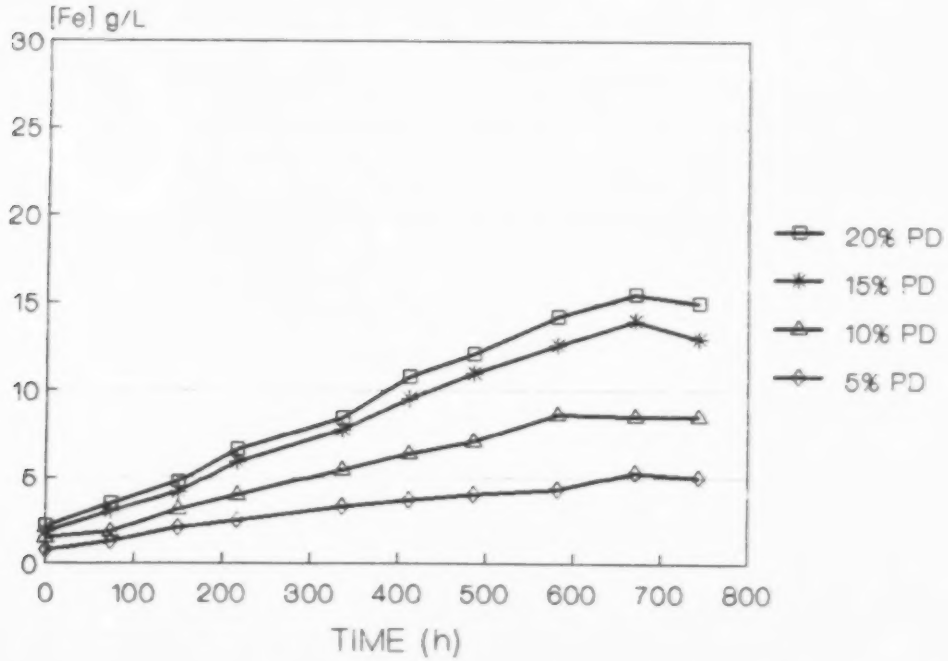

Fig. 7a Leaching of CIN concentrate with T. ferrooxidans at varying pulp density

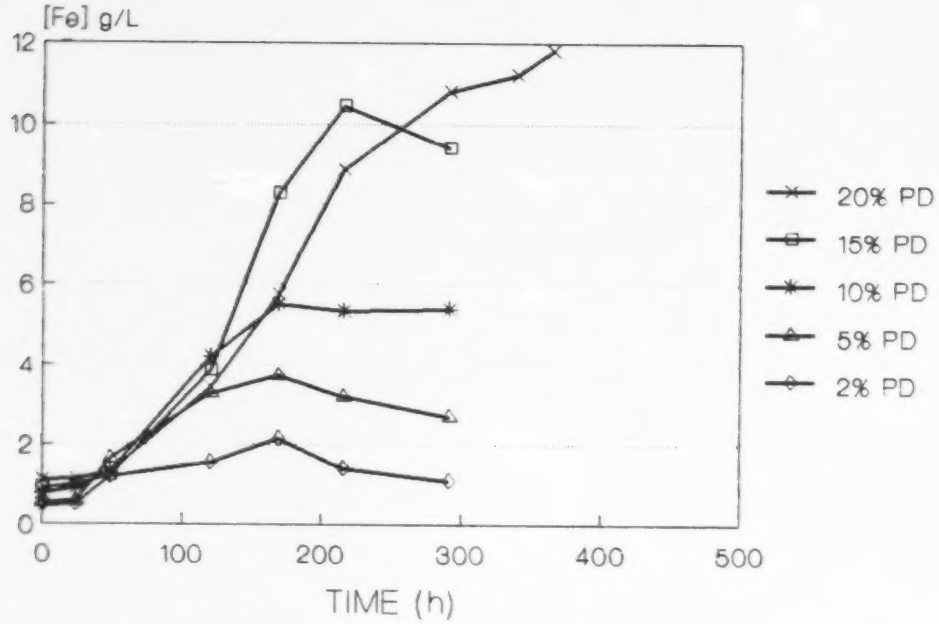

Fig. 7b Leaching of CIN concentrate with Sulfolobus at varying pulp density

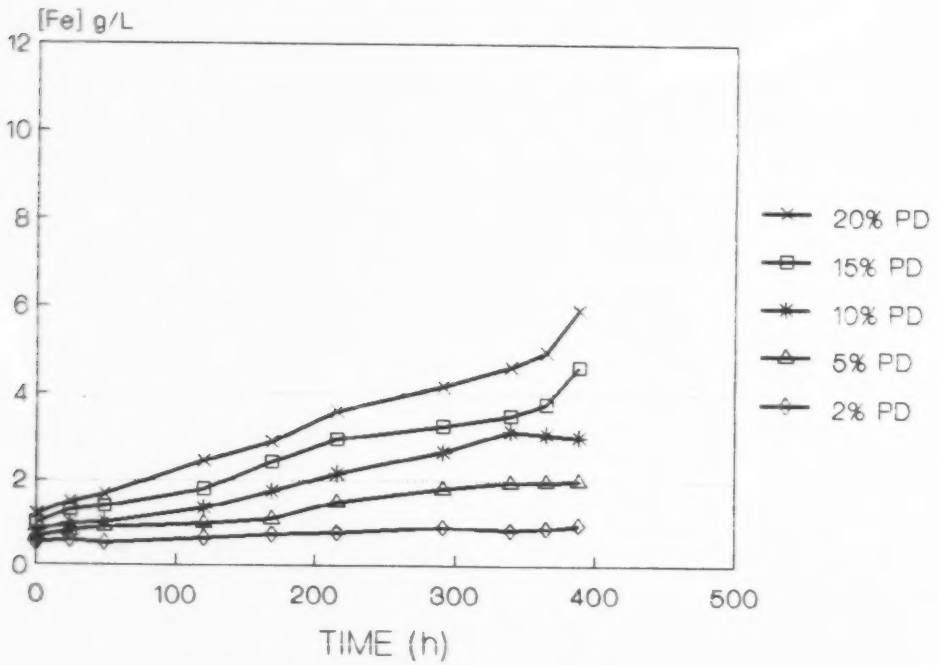

Fig. 8 The effect of pulp density on the leaching of NN concentrate with Sulfolobus and T. ferrooxidans

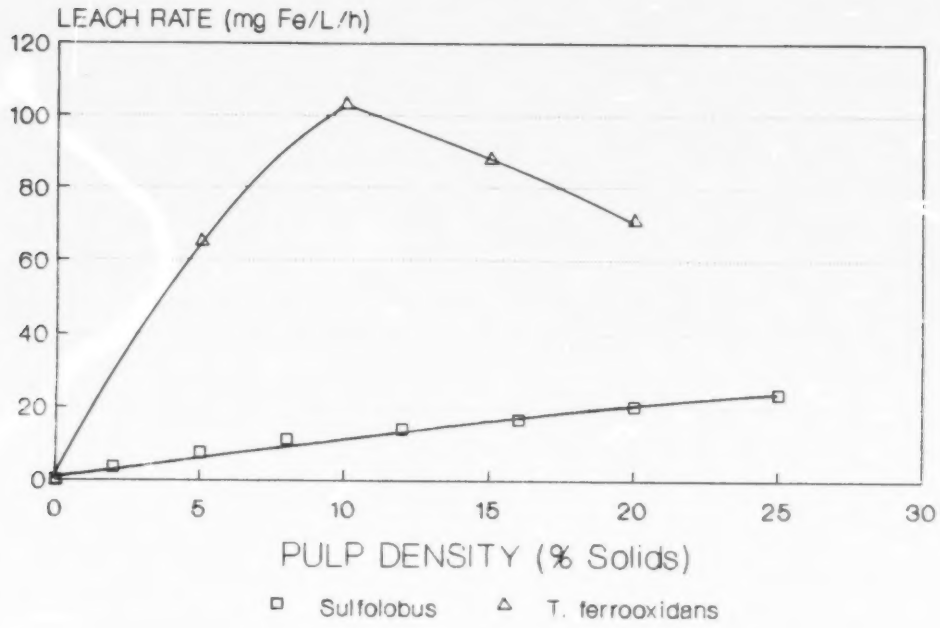

Fig. 9 The effect of pulp density on the leaching of CIN concentrate with Sulfolobus and T. ferrooxidans

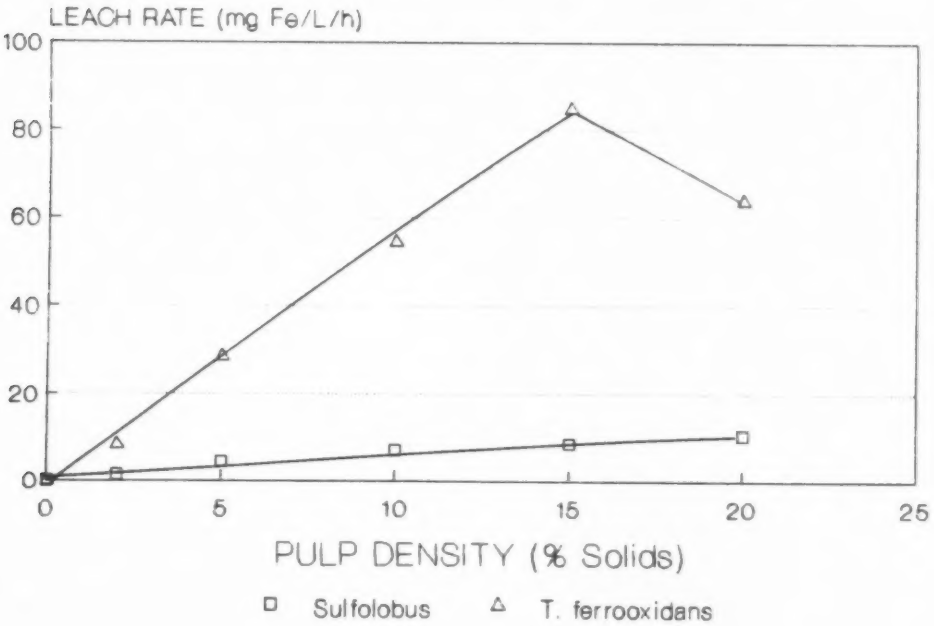

Fig. 10 The effect of carbon dioxide on the leaching of NN concentrate with Sulfolobus

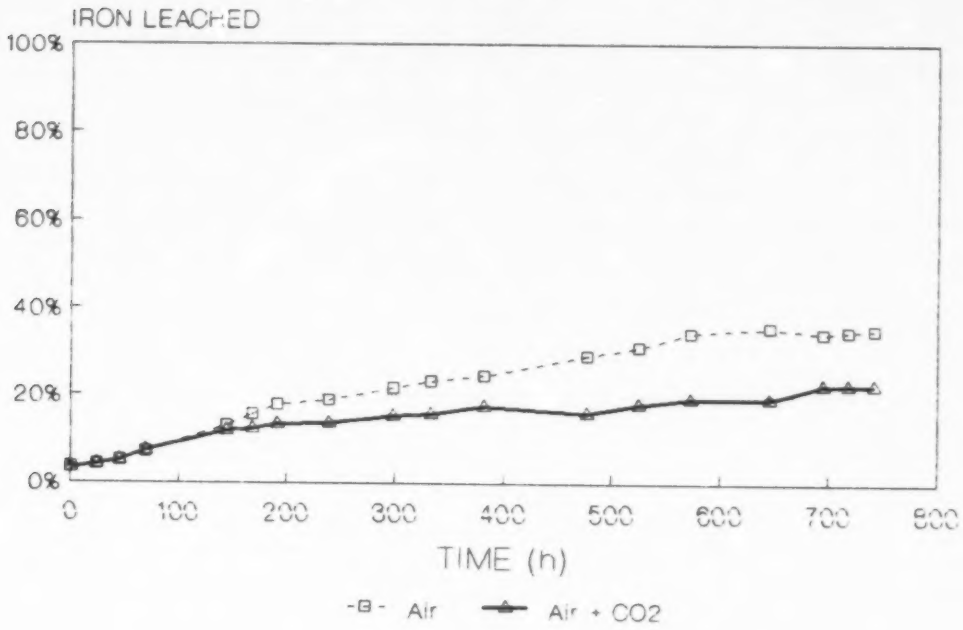

Fig. 11 Schematic flowsheet for biooxidation process

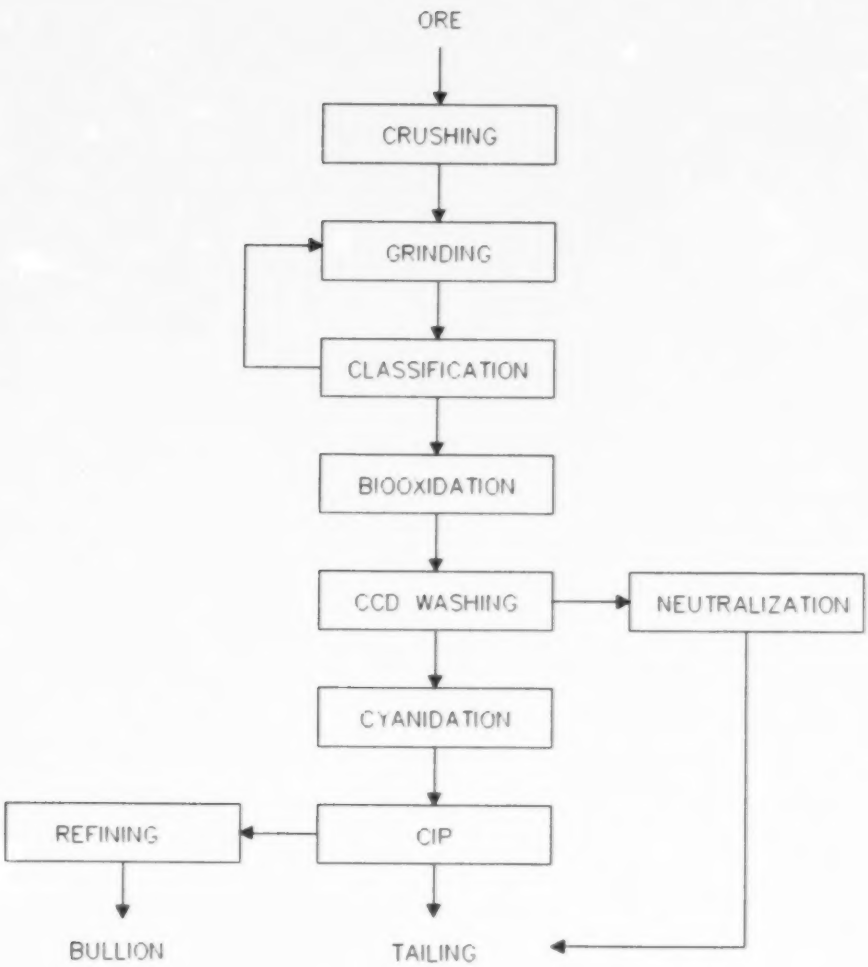

Fig. 12 The effect of cooling water temperature on capital cost of cooling system

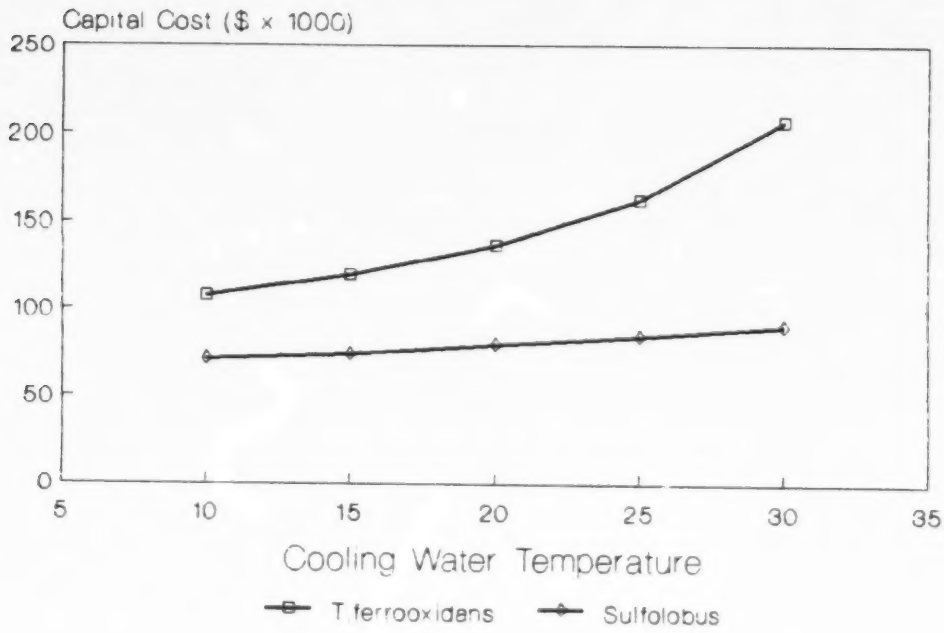

Fig. 13 The effect of cooling water temperature on the operating costs of cooling system

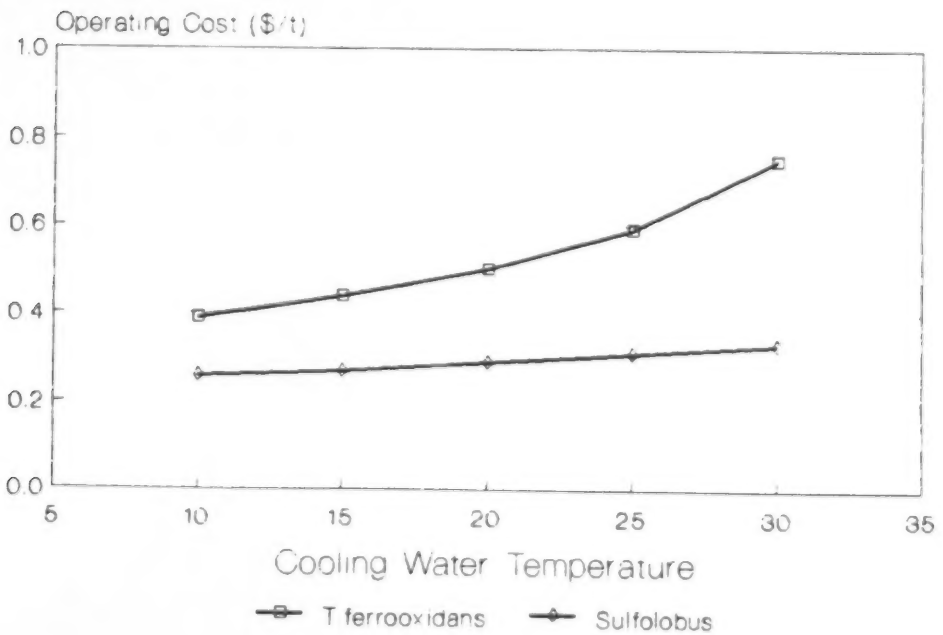

Fig. 14 The effect of kinetics on capital costs of biooxidation plant at 30% solids

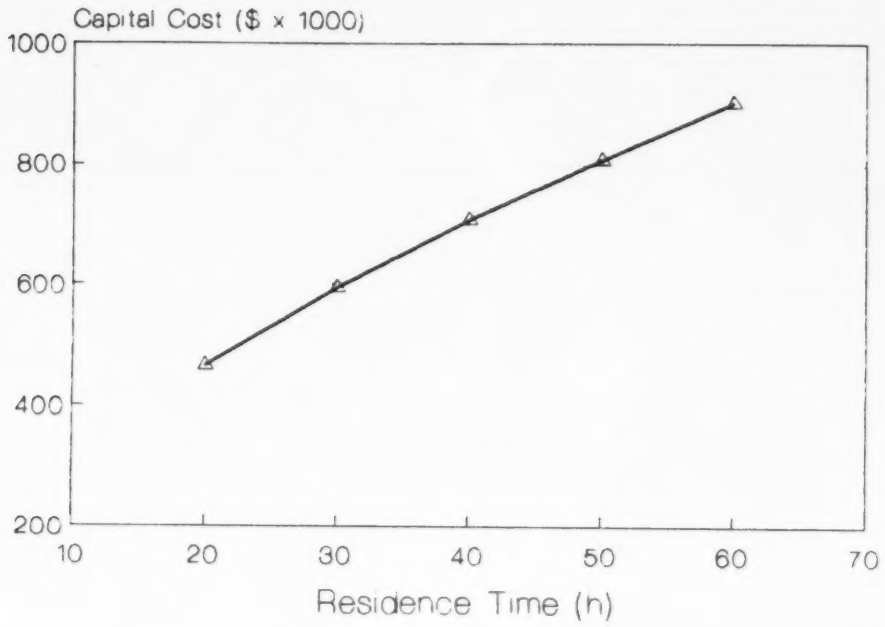

Fig. 15 Effect of kinetics on operating costs of biooxidation plant at 30% solids

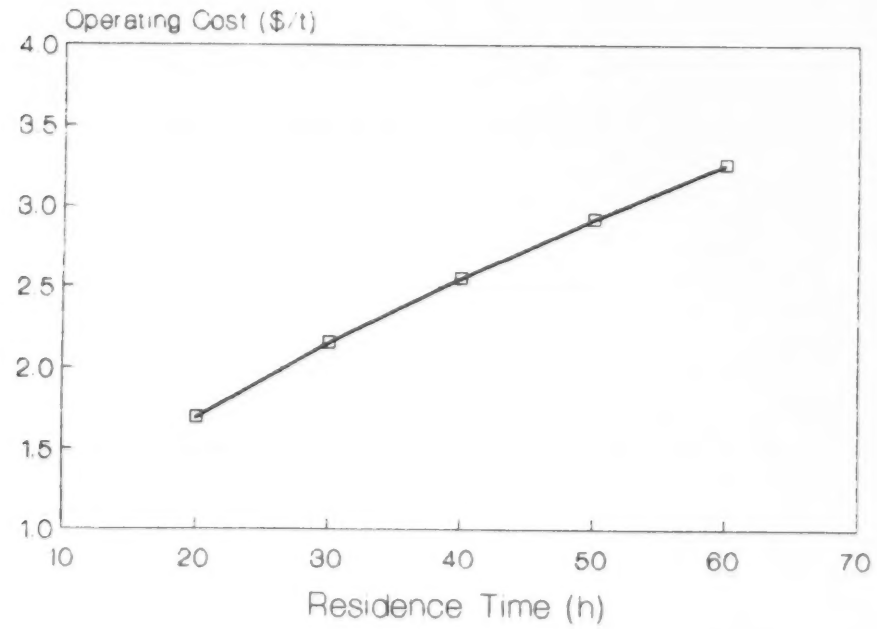

Fig. 16 Effect of kinetics and pulp density on capital cost of biooxidation plant

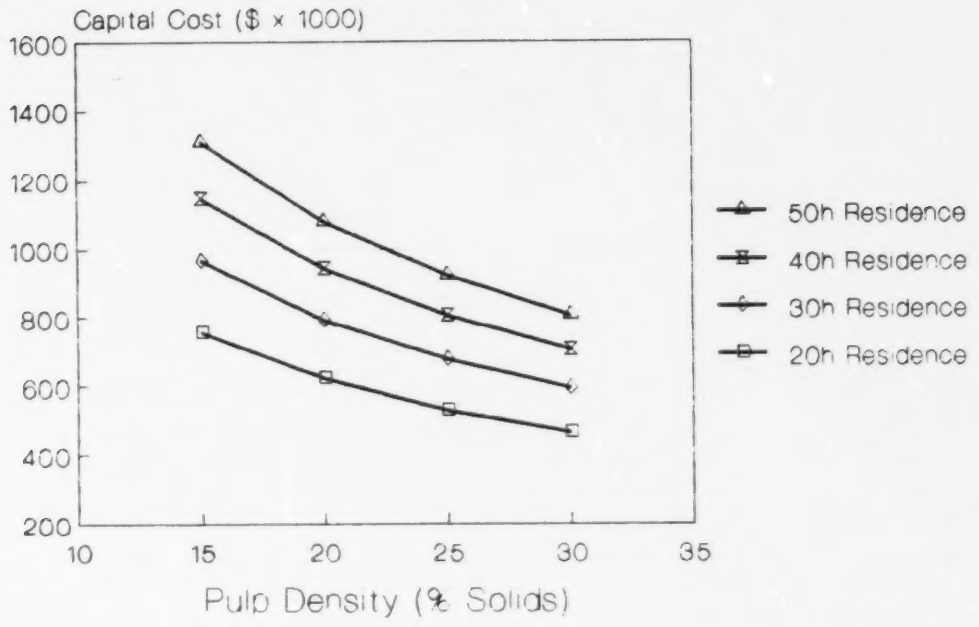

Fig. 17 Effect of pulp density and kinetics on operating cost of biooxidation plant